The J. & P. Switchgear Book

an outline of modern switchgear practice for the non-specialist user

by

R. T. Lythall, M.I.E.E.

Published by

JOHNSON & PHILLIPS LTD.

Charlton, London, S.E.7.

Electrical Engineers and Cable Makers. Establis

First edition		1927
Second edition		1930
Third edition	*Vol I*	1938
	Vol II	1942
Fourth edition		1946
Fifth edition		1953
Sixth edition		1963

PREFACE TO THE 6th EDITION

In the ten years which have passed since the fifth edition appeared, so many changes have taken place in the design and application of power switchgear that nearly all the chapters required revision and many had to be completely rewritten. The result is to be seen in this new edition which is as up-to-date as is possible in this progressive section of the electrical industry. Even so, it is feared that because of the inevitable time lag which must occur in the production of a book of this magnitude between the original work of composition and the date of publication, some descriptive detail may already be modified or even superseded. It is known for example that several British Standards referred to or quoted in the book are under review by various technical committees and new, revised issues may be expected which could modify parts of the present text.

In the preparation of this new edition, the opportunity has been taken to re-arrange the order of chapters so that those at the beginning relate to a number of theoretical aspects which lead to subsequent chapters on design and descriptive detail. Because of the supreme importance in any switchgear installation of the circuit interrupting device, be it a fuse or circuit-breaker, quite a considerable portion of the book has been devoted to a study of these devices, to their application, and to the calculations necessary for a correct choice in so far as breaking capacity is concerned. On this occasion, short-circuit calculations have been divided into two chapters, one for symmetrical faults, the other for unsymmetrical faults. In dealing with the former, considerable revision and extension has been made, firstly to simplify the task of making calculations by the inclusion of a series of tables giving the resistance and/or reactance of machines, transformers and cables (the latter in per yard terms) on a common base, i.e., 100 000 kVA, so that many individual calculations are eliminated, and secondly, to lay greater emphasis on the need to include in the calculations *all* the factors tending to limit the fault current, particularly the marked effect of resistance introduced by cables in medium voltage networks.

Another chapter which has been completely rewritten is that on protective gear, it being felt that in earlier editions too little attention was given to the relatively simpler forms of protection which would be of major interest to many readers. The revised chapter remedies this but the more elaborate forms have still been noted in some detail. References to the application of induction type relays have been brought into this chapter instead of being considered separately.

To allow for expansion in the foregoing directions, some omissions have been necessary so that the size of the book could be kept within reasonable bounds. What to omit has not been an easy choice and some criticism may be expected. The reader will note that the omissions include the chapters on D.C. Switchgear, Supervisory Remote Control (on the grounds that this is in the realm of telecommunications), Voltage Regulators (because they are not really switchgear although often mounted on the control board) and Flameproof Switchgear (because the author has covered this in another recent book).

The theme of all previous editions has been maintained, namely to provide an outline of British switchgear practice for the non-specialist user

and for students and beginners. As previously too, the book is not a mere catalogue of the practice of one manufacturer and the reader will find innumerable references to the practice and designs of a host of manufacturers, to whom incidentally the author expresses acknowledgment here as a whole, and by name elsewhere. Indeed, the information put at his disposal so freely by his many friends in the switchgear industry has been so extensive as to be embarrassing in that it has been extremely difficult to know how best to use so much data within reasonable space and inevitably much of interest has had to be left out.

As in earlier editions, two examples taken from the author's book "Calculations of Fault Currents" (Sir Isaac Pitman & Sons Ltd.) have been used in Chapter III and, on this occasion, two from his book "Simplified Short-circuit Calculations" (The Belmos Co., Ltd.). Both sources are gratefully acknowledged and to the latter firm, their kindness in allowing the author to devote so much time whilst in their employ to the preparation of this new edition.

Many suggestions resulting in detail improvement in various chapters have been received from the management and members of the J. & P. Switchgear Department, notably Mr. F. G. Bale and Mr. J. B. Davies. The work of deciphering and interpreting the handwritten manuscripts and seeing the book through the press has been most ably undertaken by Mr. C. A. Worth of the J. & P. Publicity Department. To all these the author expresses his thanks. Finally, he acknowledges the encouragement given by Messrs. Johnson & Phillips Ltd., on whose initiative the work has been undertaken and produced.

It is hoped that the usefulness of the book, so clearly established in the five earlier editions, has been at least maintained and perhaps increased in this new edition.

R.T.L.

Weymouth, Dorset. 1963

LIST OF CHAPTERS

LIST OF APPENDICES

ACKNOWLEDGMENTS

As indicated in the Preface, the author has received most valuable assistance from many outside sources in the preparation of this edition. This is particularly so in the case of switchgear manufacturers who have not only provided data concerning their product but also photographs and line drawings with which to illustrate the text. Here the author would place on record his acknowledgment to all of these, and others, by name, as follows:—

Alcan Industries Ltd.
Associated Electrical Industries Ltd.
(Switchgear and Cable Divisions)
The Belmos Co., Ltd.
The British Aluminium Co., Ltd.
British Short-Circuit Testing Station Ltd.
Brown-Boveri British Ltd.
Brush Electrical Engineering Co , Ltd.
Centro Elettrotecnico Sperimentale Italiano Giacinto Motta
The Copper Development Association
Crompton Parkinson Ltd.
E.M.P. Electric Ltd.
The English Electric Co., Ltd.
(Switchgear, M.R.I. and Fusegear Divisions)
Everett, Edgcumbe & Co., Ltd.
Geo. Ellison Ltd.
General Electric Co., Ltd.
Institution of Electrical Engineers
Long & Crawford Ltd.
W. Lucy & Co., Ltd.
N.V. tot Keuriag van Electrotechnische Materialen
Nalder Bros. & Thompson Ltd.
Parmiter, Hope & Sugden Ltd.
Permali Ltd.
Sir Isaac Pitman & Sons Ltd.
A. Reyrolle & Co., Ltd.
Switchgear & Cowans Ltd.
Switchgear Testing Co. Ltd.
South Wales Switchgear Ltd.
Yorkshire Switchgear & Engineering Co., Ltd.

Throughout the book, the source of information is noted either in the text or in the captions accompanying the illustrations or both.

Quotations from, or references to, British Standard Specifications are noted in the text and acknowledgment to the British Standards Institution is hereby made.

CHAPTER I

INTRODUCTION

CHAPTER I

INTRODUCTION

ALL electrical power needs some form of switchgear in order that it may be safely controlled, regulated or switched on or off under both normal and abnormal operating conditions. In the home or office a simple tumbler switch with a fuse somewhere in the background serves to control and protect lights, domestic apparatus or other equipment and is in its own way a form of switchgear. At the opposite end of the scale, in power stations and substations of many kinds, switchgear to serve exactly the same purpose must exist although of necessity it will have many additional and more complex features.

Between these extremes there is available a considerable range of types, designs and ratings and it can be said with truth that of the many branches of electrical engineering, few can compare in complexity of detail, or comprise so many individual yet related parts, or take on such a variety of form, layout and make-up, as electrical switchgear.

Over the years, many factors have contributed to the expansion in design and application. Not the least among these is the establishment of grid networks and the ever increasing use of electricity, the research which became possible with the building of high-power test plants for the proving of circuit-breakers and other apparatus, and fundamental research by such bodies as the Electrical Research Association.

Switchgear is a subject which cannot possibly be exhaustively dealt with in one book. It is indeed quite impossible to attempt even to describe all the known arrangements, designs and variations. Once considered a necessary evil to be given scant thought, switchgear is now acknowledged as a separate specialised science with many branches, requiring the attention of engineers trained in the art of design and application and having much more than a passing knowledge of the plant to be controlled. As comparisons between examples illustrated in this edition and those in earlier issues will show, it is a science which does not stand still, new and better designs being constantly introduced almost before previous advances have been fully absorbed. In this book therefore we must content ourselves with an outline of switchgear practice both in design and application leaving the reader to study in greater detail the multitude of individual papers and books, some of which are noted in the chapter bibliographies.

Many claims have been made from time to time concerning the advantages or disadvantages of one type of switchgear against another. Where possible, these will be noted as we proceed but no attempt will be made to influence a choice as so much depends on local circumstances and on personal preference. For example, claims for and against compound-filled gear or the alternative form with air-insulation have been made over and over again. Both have advantages and both have adherents; there are situations where one type is obviously the better choice and sometimes the

choice is not one of technical merit. As we shall see, even in any one type, variations in the method of achieving the same object occur, as for example in the method used to isolate the circuit-breaker, which can be either vertical drop-down, vertical lift-up or horizontal drawout. How does one choose?

In other situations, will a fuse-switch suffice or must a circuit-breaker be used? And if the latter, shall it be of the oil-immersed type or an air-break design?

Even with smaller details there are divergent demands as for example in the size and type of indicating instruments. Many consider that a 4 inch instrument is ample but there are others who require one which can be read at 20 feet! Shall the instrument, whatever its size, be round or square, flush mounting or projecting, long or short scale?

At the higher voltages of power transmission, a choice has to be made between indoor or outdoor (up to say 33 kV) or between oil or air-blast circuit-breakers. At the very high voltages, present tendencies lean towards the air-blast type but it must be remembered that the oil circuit-breaker is, as far as British designs are concerned, second to none, well-proved and tried, and giving little if any trouble. Any review of electrical troubles when British oil circuit-breakers have been used would produce no cause for apprehension. Nevertheless, the type is bulky, requiring a considerable oil content, and a demand for other designs arises and must be respected. This has led to the air-blast types, popular on the Continent for many years, and British developments in this field are noted in a later chapter, developments which were essential in any case to enable British manufacturers to meet Continental competition in export markets.

It may be noted here that while the quantity of oil in an oil circuit-breaker may be a disadvantage, the air-blast type is not without corresponding failings. For example, a supply of air at high pressure, in ample quantity and thoroughly dry, is a most important essential. Failure of the source of air supply will render the gear quite useless and this leads to the necessity of duplicating the source of supply, an expensive item in a small switching station. Air leakages, condensation and other problems, add to the factors which must be taken into account.

Many of the chapters which follow will discuss the pros and cons of the foregoing without bias in favour of any type.

It is not so many years ago that "breaking capacity" (or as it was then termed "rupturing capacity") was a thing of some mystery in relation to circuit interrupting devices. Today, in all countries of electrical importance, short-circuit test plants exist and the assignment of a breaking and making-capacity rating is something which can be backed by proving tests. The user of switchgear can call for evidence to substantiate the claims of manufacturers, such evidence taking the form of a certificate of rating against tests made to a standard specification. However, before a user can specify his requirements to suit his system, he must first assess with accuracy the fault values which can arise and because of the importance of making calculations for this purpose two chapters are devoted to the subject, one covering the symmetrical condition of fault on which circuit-breaker selection is made, the other covering the unsymmetrical condition where a fault does not embrace all phases of a three phase system.

CHAPTER II

A.C. CIRCUIT INTERRUPTION THEORY

CHAPTER II

A.C. CIRCUIT INTERRUPTION THEORY

Of all the many items which go to make up a complete switchgear unit, it is the circuit breaking device itself which determines the safety or otherwise of the electrical system and the plant connected thereto. It is therefore appropriate to start this book with an outline of the theory of a.c. arc interruption.

To interrupt a circuit where the load conditions are normal is not a difficult problem as the current to be broken is relatively small, amounting generally to a few hundred amperes or, in a lesser number of cases, to two thousand amperes or so. Equally important is that the power factor will be high, e.g. 0·8. But when a fault occurs on the system the short-circuit current resulting may be many times greater, as will be demonstrated in Chapters III and IV, reaching a value of tens of thousands of amperes at very low power factors (0·15 or less in some instances). Such conditions obviously must not be allowed to persist and it is the duty of the circuit interrupting device, installed at an appropriate location, to open and clear the fault from the system as quickly as possible.

The designer of these devices requires to know just what goes on in the process of arc interruption if he is to produce a design which he may confidently submit to specified proving tests (see Chapter V). This knowledge must cover the period of time from the instant of short-circuit to the instant, only fractions of a second later, when the arc is interrupted. These all important fractions of a second have been the subject of major research the world over for many years and, in Great Britain, a foremost part has been played by the Electrical Research Association, a statement which can be verified by a study of the book "Circuit-Breaking" which describes the work of the E.R.A. back to the year 1920. In spite of all that is known today, however, there is still much to be learned particularly in regard to the physics of circuit-breaker behaviour and gaseous conduction. In the space of a single chapter it is impossible to do more than outline the processes of arc interruption in circuit-breakers, leaving fuses to be considered in Chapter XII.

Every circuit-breaker, be it oil, air-break or air-blast, comprises a number of pairs of mating contacts, each pair having a fixed and moving member. Normally, these are closed to carry the load current, but arrangements are made whereby, under predetermined conditions, these contacts separate automatically to interrupt whatever current is flowing. The number of pairs of contacts per pole may vary in different designs but in the oil-break type the majority of circuit-breakers have two such pairs per pole and such a breaker is designated double-break. Designs do exist however, particularly at the higher voltages, where four and even six breaks per pole are employed. Some designers on the other hand favour a single-break design which has only one pair of mating contacts per pole based on the theory that in a

double-break arrangement some 83 per cent of the duty of interruption is performed on one break.

When contact separation occurs, an arc is drawn between the fixed and moving contacts and at high currents this arc is essentially a column of gas which has an exceedingly high core temperature. The heat of the arc causes the oil in an oil circuit-breaker to decompose to liberate gases comprising hydrogen, acetylene, methane, ethylene and other hydrocarbons, the actual proportions of which will vary in relation to current and pressure,

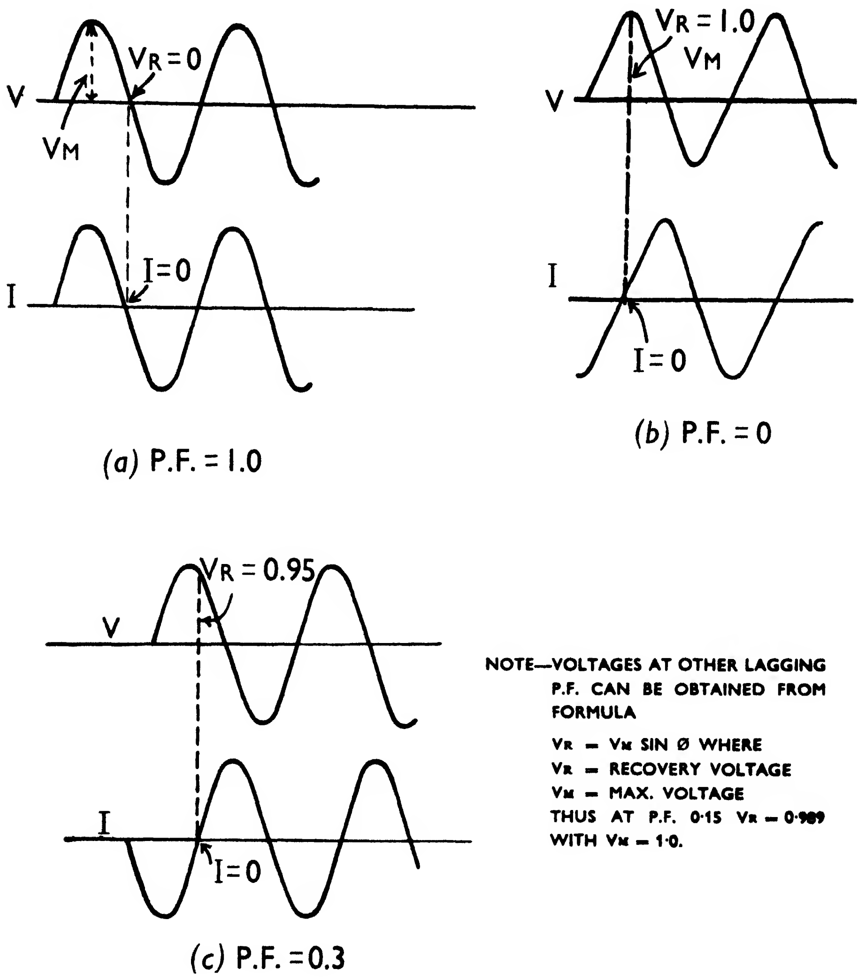


FIG. 2-1.—*Illustrating the variation of recovery voltage with power factor.*

but average values may be assumed of 70 per cent hydrogen, 20/25 per cent acetylene and 5/10 per cent all others. Due to the high temperature, the acetylene, ethylene and methane disassociate leaving the arc maintained in a column of hydrogen.

In air circuit-breakers (which incidentally are normally single-break) the arc exists in a mixture of air and metallic vapour.

The problem of interrupting an a.c. arc in any type of circuit-breaker, may be stated briefly and in very broad terms as that of providing means whereby the highly conductive gaseous path is deionized to such an extent that on current interruption the dielectric strength in the arc gap exceeds the increasing voltage impressed on the gap tending to re-establish the flow of current. An opportunity for the dielectric strength to recover occurs twice in every cycle when the current passes through zero and, in the ideal circuit-breaker, interruption of fault current would be achieved at the first current zero following the initiation of the arc. This ideal is not always achieved as many factors are involved in the process of deionizing the arc path and, depending on the design and type of circuit-breaker, there may well be several cycles of arcing prior to final extinction.

The process of deionization is aided in a number of ways such as lengthening, generation of high gas pressure, turbulence and arc splitting, the latter being effectively a means of lengthening the arc. Various forms of arc-control device will be described in Chapter VI, the purpose of which is to assist one or more of these processes. In the air-blast designs air is directed at high velocity into or across the arc path and although air has a lower dielectric strength than oil, its effectiveness is not less because of the higher velocity with which it can be forced across the arc path.

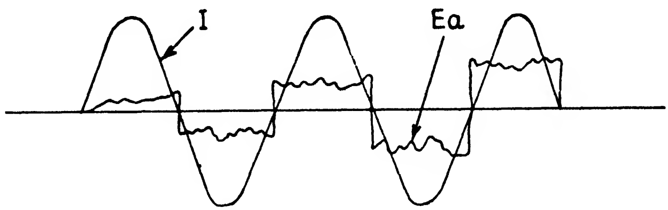
The voltage impressed across the arc gap at current zero will depend on the power factor of the circuit up to the fault and where this is high, say 0·8 or 0·9, the breaker will only have to deal with some value of voltage considerably less than the peak value. This is generally the condition when a circuit-breaker has to interrupt normal load current or fault currents at electrically remote points on a network where resistance (mainly in cables) ensures a high or relatively high power factor. At points nearer to the source of power however, the power factor is very nearly zero under fault conditions giving virtually peak voltage at current zero. This is demonstrated in Fig. 2-1 for zero, 0·3 and unity power factors.

In a paper by Harvey and Erith a set of curves has been given to show the influence of power factor on arcing times and its effect on the arc energy. These show that an increase in power factor from 0·15 to 0·3 reduces arcing time by about 10 per cent and arc energy by the same amount. On the other hand an increase from 0·15 to 0·5 gives reductions of approximately 20 and 30 per cent respectively.

During the arcing period the voltage across the contact gap is known as the arc voltage and is relatively low with heavy current arcs of short length. It is the voltage shown at Ea in Fig. 2-2 and at current zero it rises rapidly to the peak value of the restriking voltage transient. This change, not readily observable on ordinary magnetic oscillograms, has been studied in great detail by means of the cathode ray oscillograph and it is found, as shown in Fig. 2-3, to be oscillating about a zero line which is the normal 50 c/s wave of recovery voltage. The frequency of oscillation corresponds

to the natural frequency of the system and is determined by the capacitance, inductance and resistance of the system and its distribution.

In a matter of micro-seconds the oscillating voltage merges by damping into the recovery voltage at normal frequency but it is the amplitude of this oscillating voltage which is important in circuit interruption. To some degree the amplitude is affected by the peak value of the 50 c/s voltage at



I =Current
Ea=Arc voltage

FIG. 2-2.

current zero as shown in Fig. 2-1. The nature of the fault may also affect it; for example, on a three phase fault in which either the neutral or the fault, or both are not earthed, the instantaneous voltage across the first phase to clear will be 50 per cent greater than the line to neutral peak. This is demonstrated in Fig. 2-4 where the blue phase has cleared while the yellow and red phases are still connected via the arcs across the contacts.

Thus the amplitude of this oscillating voltage (termed the restriking voltage) may reach an instantaneous peak of 2.1·5 phase to neutral volts.

The oscillating voltage in Fig. 2-3 is shown as having a single frequency

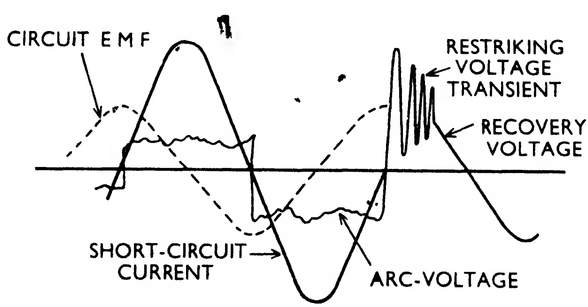


FIG. 2-3.

transient. In practice two or more frequencies may be present resulting in a composite frequency such as that shown in Fig. 2-5.

We have noted that the amplitude of the restriking voltage has a bearing on the work to be performed by the circuit-breaker and now it must be noted that the rate of rise of this voltage (known in short as R.R.R.V.) also affects the severity. The rate of rise is stated in volts per micro-second and is

obtained by drawing a straight line through zero and tangential to the point of the curve. For a single frequency transient as in Fig. 2-3 this presents no difficulty but where, as in Fig. 2-5, more than one frequency appears, the several peaks may each have a different rate of rise and the greatest rise and the greatest rate of rise may not be associated with the peak of greatest amplitude.

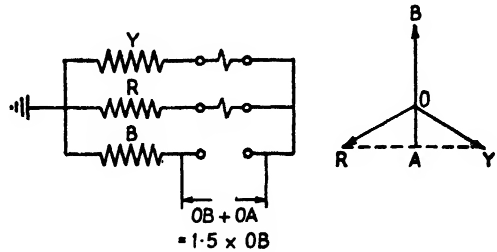


FIG. 2-4.

The natural frequency of an oscillating circuit is:—

$$Fn = \frac{1}{2\pi\sqrt{LC}}$$

so that the Fn will be low for short-circuits at the remote ends of feeders as capacitance will be high, whereas at points near to the busbars of a power station and at points close to power transformers, capacitance will be a minimum, Fn will be high, and the interrupting conditions severe.

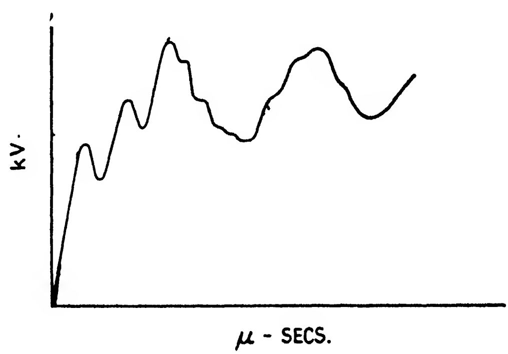


FIG. 2-5.

In circuit interruption by air-blast, restriking voltage plays an important part in that the circuit-breaker is sensitive to this transient. For this reason, what is described as resistance switching has been resorted to in axial blast designs. Resistance damps the oscillation and this has been used to advantage by switching-in resistance during the arcing period. In air-blast breakers with cross blast, the problem is solved largely by the resistance of the long arc which is drawn across splitter devices.

With the insertion of resistance, the frequency of oscillation becomes:—

$$Fn = \frac{1}{2\pi}\sqrt{\left[\frac{1}{LC} - \left(\frac{1}{2\,RC}\right)^2\right]}$$

From this it follows that, if the resistance is given a value less than $\frac{1}{2}\sqrt{L/C}$, the oscillatory nature of the transient vanishes and the rate of rise of restriking voltage is kept within the rating of the breaker.

In resorting to resistance switching, the usual procedure is to connect the resistance in shunt with the arc (see Chapter VIII, Fig. 8-10 for example). With the arc so shunted, a part of the arc current is diverted to and flows through the resistance.

This results in a decrease of the arc current and an increase in the rate of deionization of the arc path and in the resistance of the arc. This leads to a further increase in the current through the shunt resistance and so the build-up proceeds until the current path through the arc is substituted by that through the resistance either wholly or in the greater part. In the latter case, the small value of current remaining in the arc path becomes so unstable that it is easily extinguished by an air-blast and the current which continues to flow through the resistance is readily broken by the series isolator. Alternatively, the resistance may be automatically switched in by transference of the arc from the moving contacts to a probe contact, as shown in Fig. 2-6, and current flowing at stage (d) will have a high power factor so that it is quickly extinguished by the air-blast. When discussing air-blast circuit-breakers later in Chapter VIII we shall note how shunt resistors have another purpose, i.e., to ensure equal voltage distribution across multiple interrupting heads per pole.

From what has been said it is clear that with either a high rate of rise or a high peak amplitude of restriking voltage independent restriking of the arc is possible. In the former case the arc path has not had time to cool and deionize sufficiently, hence the arc may restrike with only a low peak value of restriking voltage. In the latter case, the peak value may be high enough to flash over the gap between the contacts even though, due to a low rate of rise, the arc path has been able to cool and deionize.

It has been noted that anything which aids deionization at current zero and immediately after is important in reducing the clearance time of a circuit-breaker under fault conditions. To have this same aid available at times other than at current zero can, however, have detrimental effects and, as we have said, current interruption at any other time is not desired or desirable. For example, the air-blast circuit-breaker is particularly sensitive to what is known as "current chopping" which means simply that the current is forced to an unnatural zero and interrupted at a time before the natural zero pause in the cycle. The effect of this is a practically instantaneous collapse of the current and it can lead to serious over-voltages which may affect the whole system. This problem is acute when the circuit-breaker has to deal with very low values of current such as transformer magnetising currents and capacity (line charging) currents. The cause lies generally in the fact that in air-blast circuit-breakers, the full pressure of air is available at all times and in an I.E.E. paper presented by Cox and Wilcox (see bibliography) it is stated that:—

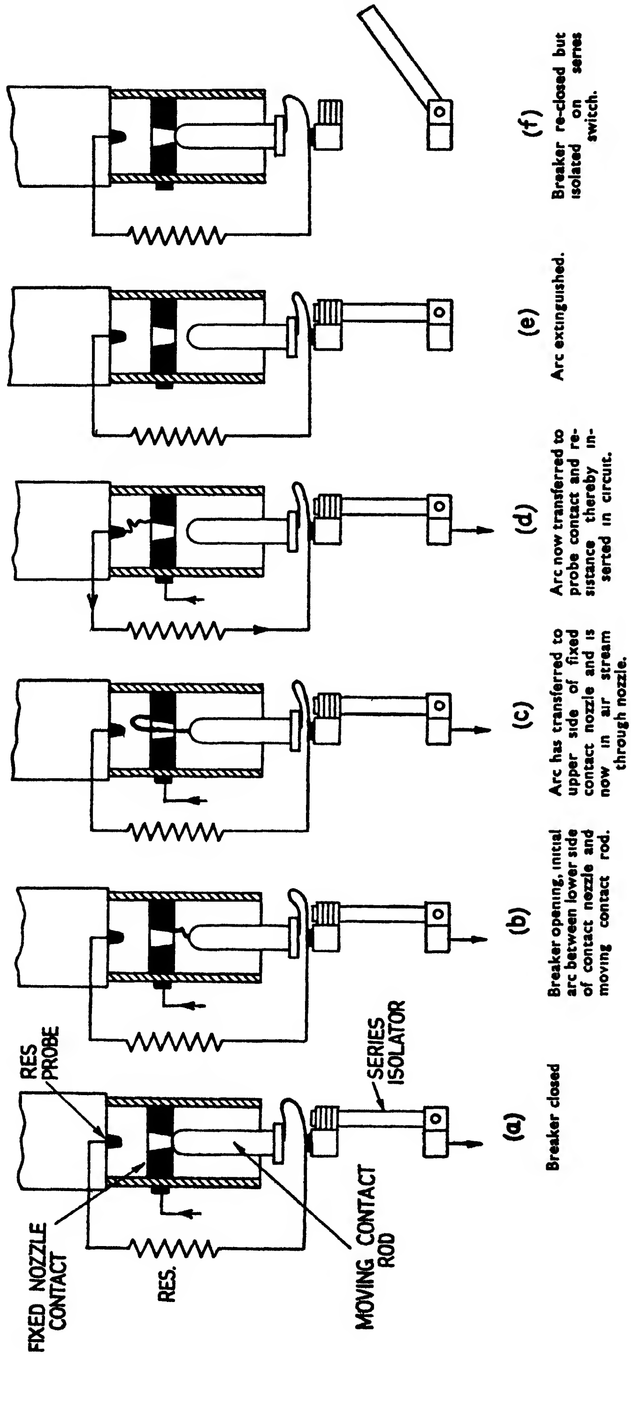


FIG. 2-6.—*Sequence diagram of resistance switching in an air-blast circuit-breaker.*

"As the 50 cycle current being interrupted approaches zero, a value is reached at which deionization of the arc in the contact gap is so rapid that the current is forcibly suppressed before the natural zero point. If the total reactance of the circuit is such that the current to be interrupted is of the order of 150 A r.m.s. or above, this forcible suppression occurs when the current has nearly reached its normal zero. With higher values of circuit reactance giving lower values of 50-cycle current, the total amount of ionization of the contact gap is less and suppression of the current occurs earlier before the normal current zero at a higher instantaneous value, thereby inducing a higher voltage in the increased circuit inductance. With a correctly designed breaker this voltage is prevented from rising to a dangerous value by breaking down the contact gap and re-establishing the normal arc. The arc current which flows is again forcibly suppressed and the process is repeated until the current almost reaches its normal zero." This is shown in Fig. 2-7.

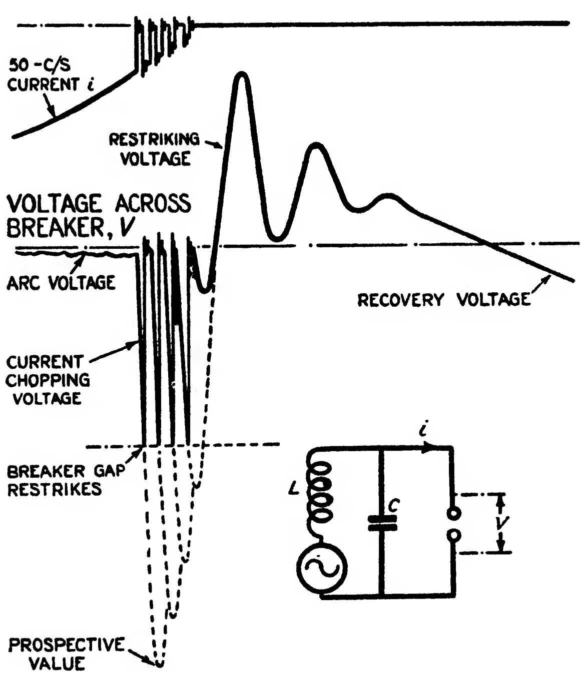


FIG. 2-7.—(*Journal I.E.E.*).

The voltage generated by current chopping may have a value several times the insulation level of the apparatus on the system and there may be failure of external insulation.

A.C. circuit interruption is a fascinating problem involving not only the more obvious mechanical and electrical aspects but also the physics of electrical gas discharges. Co-operation in research between engineers

and physicists has led to very considerable improvement in circuit interrupting devices, and later we shall see some of the results when circuit-breakers of various types are considered in detail.

Here, much of interest has been omitted simply on account of space but for the student wishing to continue the study, any of the papers or books noted in the bibliography will be invaluable. In particular two books are noteworthy, namely those by Trencham and Crane.

BIBLIOGRAPHY

Circuit Breaking, H. Trencham (Editor) (Butterworth Scientific Publications).

Electric Power System Control, H. P. Young (Chapman & Hall).

Fundamentals of A.C. Circuit Interruption, Dr. Erwin Salzer (Allis Chalmers Manfg. Co. Ltd., U.S.A.).

Switchgear Practice, A. Arnold (Chapman & Hall).

Switchgear Principles, P. H. G. Crane (Cleaver-Hume Press Ltd.).

"The Development of the Single-Break Oil Circuit-Breaker for Metalclad Switchgear," D. R. Davies and C. H. Flurschiem, "Journal I.E.E.," Vol. 79, 1936, p. 129.

"Restriking Voltage and its Import in Circuit-Breaker Operation," H. Trencham and K. J. R. Williamson, "Journal I.E.E.," Vol. 80, 1937, p. 460.

"The Proving of Oil Circuit-Breakers under Short Circuit Conditions," A. P. Harvey and H. A. Erith, "Journal I.E.E.," Vol. 88, Part I, No. 7.

"Restriking Voltage as a Factor in the Performance, Rating and Selection of Circuit-Breakers," J. A. Harle and R. W. Wild, "Journal I.E.E.," Vol. 91, Part II, No. 24, December 1944.

"The Influence of Resistance Switching on the Design of High Voltage Air-Blast Circuit-Breakers," H. E. Cox and T. W. Wilcox, "Journal I.E.E.," Vol. 91, Part II, No. 24, December 1944.

"Factors Influencing the Design of High Voltage Air-Blast Circuit-Breakers," C. H. Flurschiem, B.A., and E. L. L'Estrange, M.Eng., "Journal I.E.E.," Vol. 96, Part II, No. 52, August 1949.

"The Performance of High-Voltage Oil Circuit-Breakers Incorporating Resistance Switching," H. E. Cox and T. W. Wilcox, "Journal I.E.E.," Vol. 94, Part II, p. 351, 1947.

"The Extinction of Arcs in Air-Blast Circuit-Breakers," A. Allen and D. F. Amer, "Journal I.E.E.," Vol. 94, Part II, 1947, p. 333.

"The Evaluation of Restriking Voltages," J. R. Mortlake, "Journal I.E.E.," Vol. 92, Part II, No. 30, December 1945.

CHAPTER III

SHORT-CIRCUIT CALCULATIONS FOR SYMMETRICAL FAULTS

CHAPTER III

SHORT-CIRCUIT CALCULATIONS FOR SYMMETRICAL FAULTS

THE importance of determining the value of fault current which can arise in the event of a short-circuit on an electrical network is well known.

This knowledge is essential for the purchase of circuit interrupting devices (circuit-breakers, switches or fuses) of proved ability to deal with the short-circuit condition and to ensure that such associated apparatus as busbars, connections, current transformers etc., can withstand the electro-magnetic and thermal conditions which arise, due to the passage of the fault current, until interrupted. For these purposes the relatively simple method of calculation based on a three phase fault with symmetry is sufficient, a condition indicated in Fig. 3-1, and it is this method which will be discussed here. In the following chapter discussion will be devoted to other types of fault involving an unsymmetrical condition.

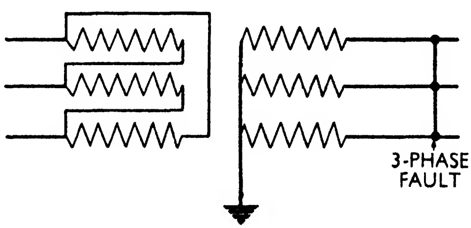


FIG. 3-1.

In any type of short-circuit calculation certain essentials must be known and appreciated. In the first place it must be noted that the source of fault power originates in all connected generating plant and may be further implemented by other synchronous machines (e.g. motors) which, while normally taking power *from* the network, may feed power *into* it under fault conditions, particularly if there is a drop in voltage or frequency. All such sources of power must therefore be considered and if of significant size must be included in the calculation.

Secondly, the magnitude of the fault current is limited only by the combined impedances of all machines, transformers, cables and (if employed) reactors. It is therefore essential to have full knowledge of the system impedances, noting that impedance is that value which combines resistance and reactance vectorially, as indicated in Fig. 3-2. Here it may be noted that in many items of plant, resistance is so small in comparison with reactance as to be unimportant and it is sufficient to deal in reactance terms only, this generally being the case for generators, transformers, synchronous motors and reactors. On the other hand resistance may be considerable in

cables or overhead lines and as will be shown can have considerable effect, particularly in low-voltage (400-600 volts) calculations. In general it may be assumed that where resistance is less than one-third of the reactance, the former may be ignored and the calculated fault value will not be in error by more than 5 per cent. If, however, the resistance is of the order of one-half that of the reactance, and resistance is ignored, errors up to 12 per cent may be introduced. By "errors" it is meant that calculations will result in values higher than is actually the case being obtained and, in some cases, lead to the purchase of gear with a higher rating than necessary.

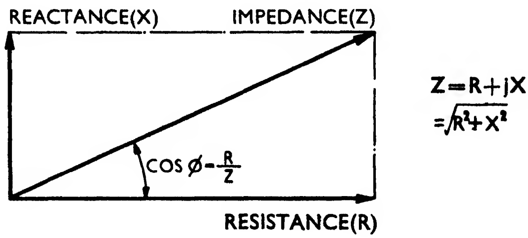


FIG. 3-2.

Resistance and reactance (and consequently impedance) may be expressed in percentage or ohmic terms. In the case of machines and transformers, manufacturers values are always in percentage terms while tables for cables and overhead lines are always in ohmic terms. Calculations can be made using either but not a mixture so that if, as in the calculations which follow, the percentage method is used, then any item with ohmic values must be converted to percentage using the formula:—

$$\begin{array}{l}\text{Percentage value on given kVA base}\\ \text{for ohmic value } \Omega\end{array} = \frac{100\,000 . \text{kVA base} . \Omega}{V^2}$$

When Ω=value in ohms (resistance, reactance or impedance)
and V=voltage between lines.

This formula introduces the term "kVA base" and needs some explanation. It arises from the fact that in many networks generators and/or transformers may be operating in parallel and may be of widely different rating (kVA). In such circumstances no common comparison can be made unless each rating is converted to a base or common value. It is quite unimportant what value is chosen for the base and it could be

(a) that of the largest machine or transformer, or
(b) that of the total plant capacity, or
(c) an arbitrary figure unrelated to any machine or transformer rating.

In what follows alternative (c) will be used as it permits any calculation to be made from tables based on a common figure and therefore these tables can be used for any combination of plant ratings without the need to select a base each time. The figure chosen for the base has no effect on the ultimate result so long as we remember to use the base kVA in the final formula to

arrive at the short-circuit MVA. The figure chosen for the purpose of this chapter will be 100 000 kVA but in working out an example later it will be shown that any other base kVA could have been chosen.

With the foregoing established, direct reference Tables 3 : 1 to 3 : 4 can be produced as follows.

MACHINES AND TRANSFORMERS

To convert the normal percentage figures as quoted by the manufacturer to equivalent values on our chosen base of 100 000 kVA, the formula used is:—

$$\text{percentage on base kVA} = \frac{\text{base kVA} \cdot \text{normal percentage}}{\text{machine or transformer kVA}}$$

Thus a machine of 20 000 kVA rating with a normal reactance of 12 per cent would, by this formula, have a reactance on a 100 000 kVA base of:—

$$\frac{100\,000 \cdot 12}{20\,000} = 60\%$$

or a transformer of 400 kVA rating with a normal reactance of 4·75 per cent would, on a 100 000 kVA base, be:—

$$\frac{100\,000 \cdot 4{\cdot}75}{400} = 1\,187{\cdot}5\%$$

We can therefore compile Tables 3 : 1 and 3 : 2 on this basis for future use in the worked examples.

TABLE 3 : 1

HIGH SPEED GENERATORS

kVA rating	Typical* normal reactance %	kV	Percentage reactance on 100 000 kVA base
1 000 2 000 5 000 7 500 10 000 15 000	12·0	up to 11	1 200 600 240 160 120 80
20 000 25 000	13·5	up to 11	67·5 54·0
30 000	15·0	up to 11	50·0
30 000	20·0	22/33	66·6

**These values are representative only and wherever possible actual values should be obtained from the manufacturer and the reactance on the base kVA calculated as indicated.*

No generalised figures can be given for slow speed generators, e.g. water wheel driven, and specific data should be obtained from the manufacturer.

TABLE 3 : 2

POWER TRANSFORMERS

kVA rating	Percentage reactance on 100 000 kVA base									
	H.V. Winding kV									
	3·3 6·6	11·0	15	22	33	44	55	66	88	110 132
100	4 750	4 750	5 000	5 000	5 000	5 500	5 500	5 500	—	—
150	3 166	3 166	3 333	3 333	3 333	3 666	3 666	3 666	—	—
200	2 375	2 375	2 500	2 500	2 500	2 750	2 750	2 750	3 000	—
250	1 900	1 900	2 000	2 000	2 000	2 200	2 200	2 200	2 400	2 600
300	1 583	1 583	1 666	1 666	1 666	1 833	1 833	1 833	2 000	2 173
400	1 187	1 187	1 250	1 250	1 250	1 375	1 375	1 375	1 500	1 625
500	950	950	1 000	1 000	1 000	1 100	1 100	1 200	1 300	1 400
600	791	791	833	833	833	916	916	1 000	1 100	1 173
750	633	633	666	666	666	733	733	800	866	933
1 000	475	475	500	500	500	550	550	600	650	700
1 250	400	400	440	440	440	480	520	520	520	560
1 500	366	366	400	400	400	440	470	470	470	500
2 000	300	300	300	300	300	325	350	350	350	375
2 500	240	240	240	240	240	260	280	280	280	300
3 000	—	200	217	233	233	233	250	250	270	270
4 000	—	150	157	175	175	175	187	187	200	200
5 000	—	120	130	140	140	140	150	150	160	160
6 000	—	117	117	125	125	125	133	133	141	141
7 500	—	93	100	107	107	107	110	110	120	120
10 000	—	—	—	90	90	90	90	90	100	100
12 500	—	—	—	80	80	80	80	80	80	80
15 000	—	—	—	70	70	70	70	70	70	70
20 000	—	—	—	50	50	50	50	50	50	50
25 000	—	—	—	40	40	40	40	40	40	40
30 000	—	—	—	35	35	35	35	35	35	35

All the figures in this table are based on average reactance values for standard transformers. If the actual value is known for any particular transformer, it should be converted to the 100 000 kVA base figure using the formula indicated earlier.

CABLES

At this point we shall be concerned only with cables for use on systems where the voltage is 3·3 kV and above, leaving those for systems in the 400-600 volt range for later consideration as it is necessary to take into account other factors.

As indicated earlier, tables as issued by cable manufacturers give values in ohms and these are in terms of per mile or per 1 000 yards.

Not only is it necessary to convert the ohmic values to percentages on our selected base of 100 000 kVA but it is often inconvenient to deal in lengths of one mile or 1 000 yards and therefore Tables 3 : 3 and 3 : 4 have been prepared on the basis of *per yard* thus permitting a simple multiplication by the number of yards in a given example.

These tables include both resistance and reactance values for the reasons noted earlier and in the worked examples later it will be shown how these are used in a calculation.

The formula on which these tables are based has been given on page 20. On the basis of per yard and a base of 100 000 kVA, any manufacturer's table giving values in ohms per 1 000 yards can be converted by the simple process of multiplying the ohmic values by one of the following factors:—

Voltage of system	Multiplying factor
400	62·5
415	58·0
440	51·5
500	40·0
550	33·0
600	28·0
3 300	0·918
6 600	0·229
11 000	0·0826
22 000	0·0207
33 000	0·009

and it is these factors which have been applied to published tables for J. & P. cables to produce Tables 3 : 3 and 3 : 4.

TABLE 3 : 3

MULTICORE PAPER INSULATED (BELTED) CABLES WITH COPPER OR ALUMINIUM CONDUCTORS TO B.S.480 : 1954.

Cable size sq. in.	Percentage resistance and reactance per yard on a 100 000 kVA base								
	3 300 V			6 600 V			11 000 V		
	Resistance		React.	Resistance		React.	Resistance		React.
	Cu	Al	Cu & Al	Cu	Al	Cu & Al	Cu	Al	Cu & Al
0·022 5	1·055	1·144	0·072 5	0·264	0·437	0·019 5	0·095	0·157	0·008 6
0·04	0·590	0·976	0·065 1	0·149	0·344	0·018 5	0·053	0·088	0·006 8
0·06	0·390	0·644	0·062 4	0·097	0·161	0·017 0	0·035	0·058	0·006 5
0·10	0·232	0·383	0·059 7	0·058	0·096	0·015 6	0·021	0·034	0·006
0·15	0·160	0·240	0·057 0	0·041	0·086	0·015 0	0·014 3	0·026	0·005 8
0·20	0·121	0·197	0·055 1	0·030	0·049	0·014 5	0·010 8	0·017 8	0·005 5
0·25	0·096 4	0·158	0·054	0·024	0·039	0·014 2	0·008	0·014	0·005 4
0·30	0·080	0·129	0·054	0·020	0·032	0·014 0	0·007	0·012	0·005 3
0·40	0·059 4	0·097	0·053	0·015	0·024	0·013 8	0·005	0·009	0·005 2
0·50	0·050	0·080	0·053	0·012 6	0·019	0·013 5	0·004	0·007	0·005 1

NOTES:— (1) *Allowances are made for lay.*
(2) *Resistance values based on a temperature of 20°C (68°F).*
(3) *Reactance values are at 50 cycles/second.*
(4) *Reactance values of all cables are for belted types. For 11 kV screened earthed types values may be increased by 5% and for 11 kV screened unearthed types by 10%.*

TABLE 3 : 4

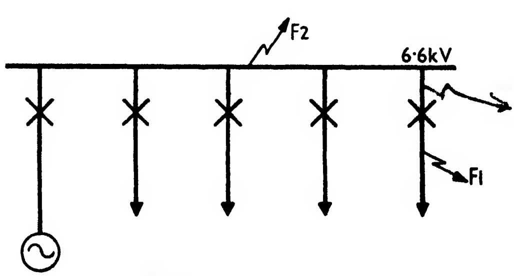
MULTICORE PAPER INSULATED (SCREENED) CABLES WITH COPPER OR ALUMINIUM CONDUCTORS TO B.S.480 : 1954.

Cable size sq. in.	Percentage resistance and reactance per yard on a 100 000 kVA base					
	22 000 V			33 000 V		
	Resistance		Reactance	Resistance		Reactance
	Cu	Al	Cu & Al	Cu	Al	Cu & Al
0·04	0·013 4	0·022	0·002 2	—	—	—
0·06	0·008 8	0·015	0·002 0	—	—	—
0·10	0·005 2	0·008	0·001 9	0·002 3	0·003 7	0·000 9
0·15	0·003 6	0·006	0·001 7	0·001 6	0·002 6	0·000 8
0·20	0·002 7	0·005	0·001 7	0·001 2	0·001 9	0·000 8
0·25	0·002 2	0·004	0·001 6	0·000 9	0·001 5	0·000 7
0·30	0·001 8	0·003	0·001 6	0·000 8	0·001 3	0·000 7
0·40	0·001 3	0·002	0·001 5	0·000 6	0·000 9	0·000 7
0·50	0·001 1	0·001 8	0·001 5	0·000 5	0·000 7	0·000 7

NOTES:—

(1) *Allowances are made for lay.*
(2) *Resistance values based on a temperature of 20°C (68°F).*
(3) *Reactance values are at 50 cycles/second.*
(4) *Reactance values are for screened cables. 22 kV cables of the belted type are available in the range 0·04-0·3 sq. in. and have reactance values approximately 8% less than for screened cables. 22 kV and 33 kV cables of the SL or SA types will have reactance values approximately 20/25% greater than for screened cables.*

With these tables available, short-circuit calculations can now be made as shown in the following worked examples, starting with the very simple system shown in Fig. 3-3. Here, a single generator is connected to a busbar system to supply a number of outgoing feeder circuits, and it is assumed



5 000 kVA GENERATOR
240% ON 100 000 kVA
FROM TABLE 3 : 1

FIG. 3-3.

that a fault (F1) may occur on one of the feeder circuits at a point close up to the circuit-breaker or alternatively the fault may occur on the busbars (F2). If the fault is at F1, then the circuit-breaker on that feeder must clear the fault, while a fault at F2 must be cleared by the circuit-breaker in the generator circuit.

In this example the only impedance to the fault is that of the generator. As noted earlier resistance (R) for generators may be assumed zero while the reactance (X) on a 100 000 kVA base is shown in Table 3 : 1 as 240%. The impedance (Z) therefore will be

$$\begin{aligned} Z &= R + jX \\ &= \sqrt{R^2+X^2} \\ &= \sqrt{0^2+240^2} \\ &= 240\% \end{aligned}$$

The formula to obtain the fault value is:—

$$\text{Short-circuit MVA} = \frac{\text{kVA base} \cdot 100}{Z \cdot 1\,000}$$

and as all our calculations will be on a 100 000 kVA base, this can be simplified to:

$$\text{S.C. MVA} = \frac{100\,000 \cdot 100}{Z \cdot 1\,000} = \frac{10\,000}{Z}$$

Therefore, for this example in Fig. 3-3 we get:—

$$\text{S.C. MVA} = \frac{10\,000}{240} = 41{\cdot}66 \text{ MVA}$$

It has been indicated earlier that the choice of kVA base does not affect the result and the simple example in Fig. 3-3 is a suitable one to use for a demonstration of this fact. Let us assume therefore that a base kVA equal to the machine rating is chosen, i.e. 5 000 kVA. In this case, the impedance will be the normal value, namely 12 per cent and we now get

$$\text{S.C. MVA} = \frac{5\,000 \cdot 100}{12 \cdot 1\,000} = 41{\cdot}66 \text{ MVA}$$

which is the value obtained when calculating on the 100 000 kVA base.

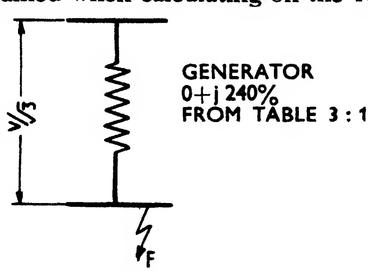


FIG. 3-4.

As a network becomes more complicated the system of impedances is more readily visualised if they are redrawn in the form of an impedance diagram. Thus in the simple example of Fig. 3-3, the impedance diagram would appear as in Fig. 3-4.

Let it now be assumed that instead of one generator there are three and that each has a different rating, the electrical system appearing as in Fig. 3-5 and the impedance diagram as in Fig. 3-6. In this example there are three impedances in parallel, each of different value and a single equivalent must be obtained equal to the reciprocal of the sum of the reciprocals, thus:—

$$\frac{1}{\frac{1}{0+j240}+\frac{1}{0+j120}+\frac{1}{0+j160}}$$

$$=\frac{1}{0+j0{\cdot}01875}=0+j53{\cdot}33\%$$

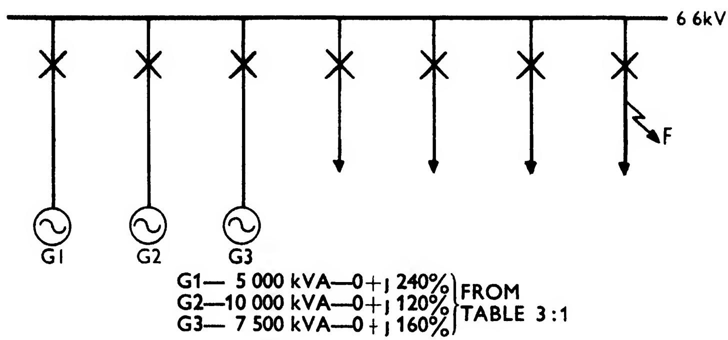


FIG 3-5

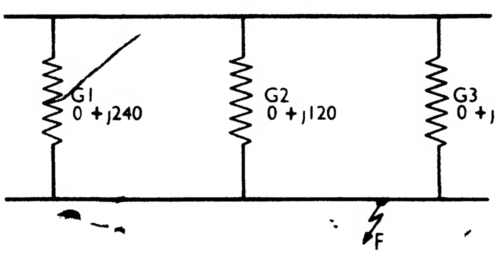


FIG. 3-6.

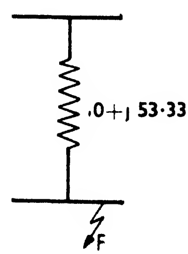


FIG. 3-7

The impedance diagram is therefore now reduced to that shown in Fig. 3-7 and the short-circuit value, assuming a fault on one of the feeder circuits at a point close up to the circuit-breaker, will be:—

$$\text{S.C. MVA}=\frac{10\,000}{Z_e}=\frac{10\,000}{53{\cdot}33}=187{\cdot}5 \text{ MVA}$$

Developing the calculations a stage further, it is assumed that one of the feeder circuits gives supply to a substation and that the cable between the two points is of 0·30 sq. in. section, the conductors being copper and the length being 1 500 yards. The electrical system is therefore as shown in Fig. 3-8 and it will be our purpose to ascertain the fault value which can

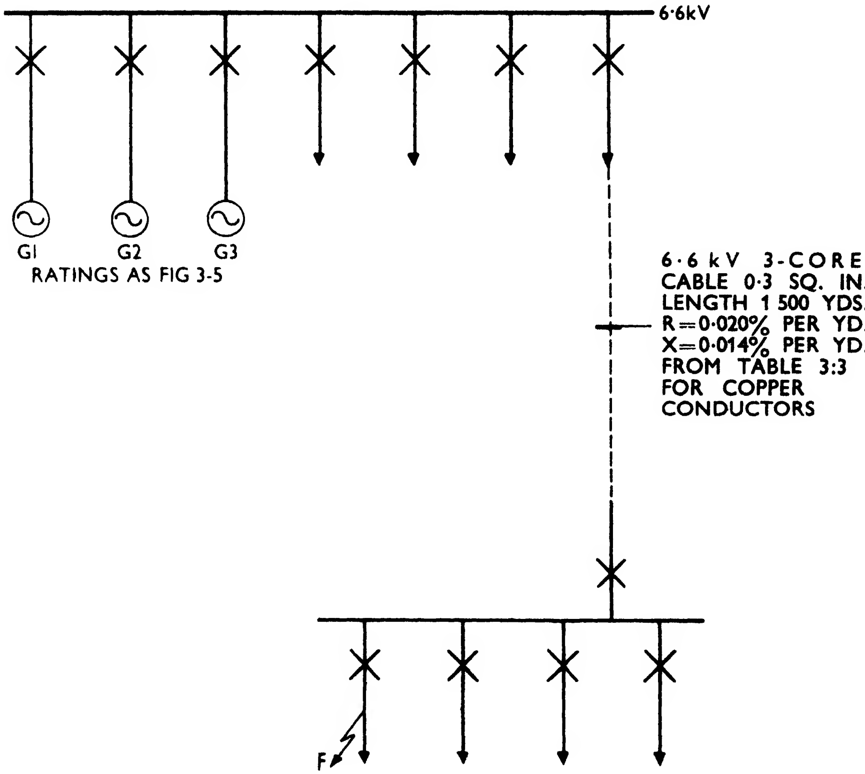


FIG. 3-8.

appear at the substation busbars as indicated. The impedance diagram for this system will be as in Fig. 3-9 comprising three impedances (generators) in parallel and one (feeder) in series. Using the data previously obtained, the impedance network can at once be reduced to Fig. 3-10 which shows two impedances in series and as these may be added arithmetically, a single equivalent diagram appears as in Fig. 3-11.

It will be noted in this example that the resistance *and* reactance factors have been taken into account in dealing with the cable and the values given

in the various diagrams have been derived from the per yard figures in Table 3 : 3 and multiplied by the length, 1 500 yards.

Fig. 3-11 shows that the total impedance to the fault is:

$$Z = 30 + j74{\cdot}33\%$$
$$= \sqrt{30^2 + 74{\cdot}33^2}$$
$$= \sqrt{6\,420} \qquad = 80{\cdot}12\%$$

and the short-circuit value at the substation busbars will be

$$\text{S.C. MVA} = \frac{10\,000}{80{\cdot}12} \qquad = 124{\cdot}8 \text{ MVA}$$

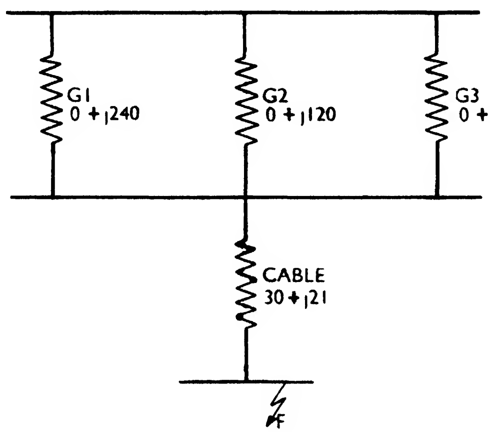


FIG. 3-9

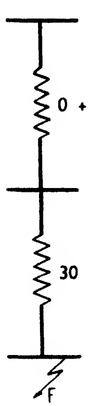


FIG. 3-10.

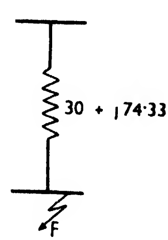


FIG. 3-11.

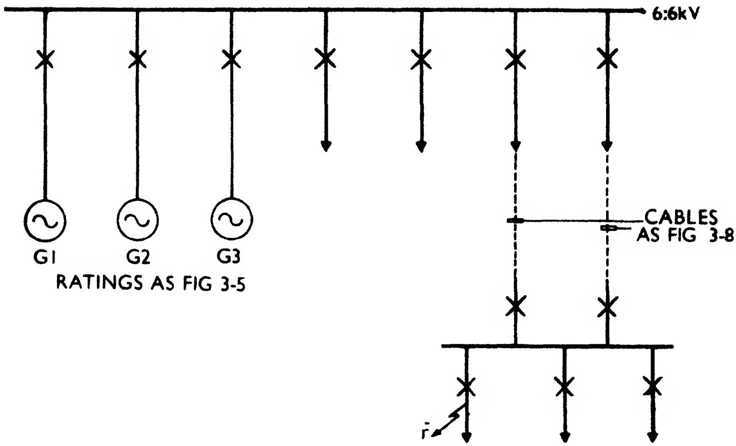


FIG. 3-12.

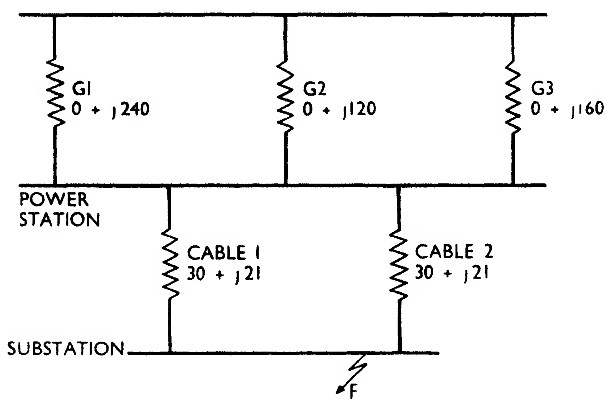


FIG. 3-13.

The approximate power factor at the fault may be deduced as follows:—

$$\text{P.F.} = \frac{R}{Z} = \frac{30}{80\cdot12} = 0\cdot374$$

At this point it is of interest to consider what effect the resistance of the cable has had on the result. Had this not been taken into account the short-circuit value would have been:—

$$\text{S.C. MVA} = \frac{10\,000}{74\cdot33} = 134\cdot6 \text{ MVA}$$

a figure nearly 7·85 per cent greater than when resistance is included.

If now it is assumed that instead of one feeder giving supply to the remote substation there are two, each of the same sectional area and length, the electrical system would be as shown in Fig. 3-12 and the impedance diagram

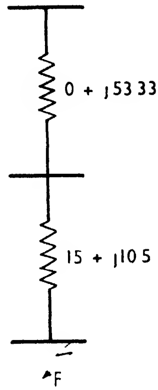


FIG. 3-14.

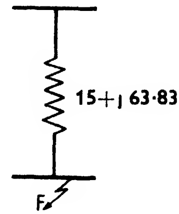


FIG 3-15.

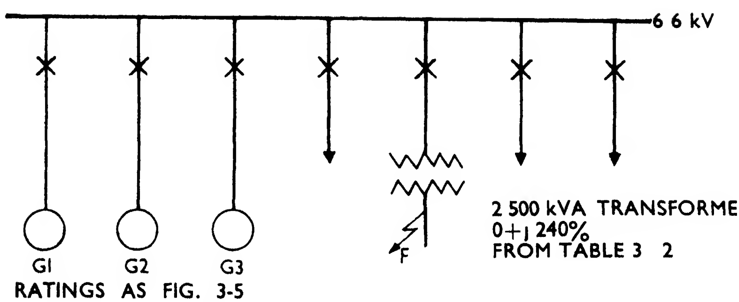


FIG 3-16

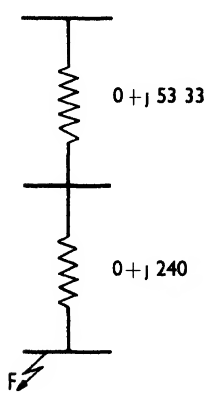


FIG. 3-17

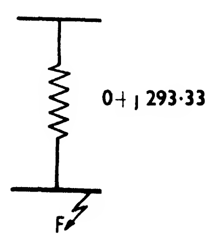


FIG. 3-18

as in Fig. 3-13. There are now two groups of parallel impedances in series; the equivalent single impedance for the generators has been determined previously by the formula given for unequal parallel impedances and while this may be used to ascertain the equivalent for the two feeder cable impedances it is simpler to note that these are equal and this being so, the equivalent value will be one-half the individual value of one cable. The impedance diagram may therefore now be reduced to Fig. 3-14 and in turn to Fig. 3-15 and the impedance to the fault will be:—

$$Z = 15 + j63{\cdot}83\%$$
$$= \sqrt{15^2 + 63{\cdot}83^2}$$
$$= \sqrt{4\,295} \qquad = 65{\cdot}53\%$$

and the short-circuit value at the substation busbars will be:—

$$\text{S.C. MVA} = \frac{10\,000}{65{\cdot}53} \qquad = 152{\cdot}6 \text{ MVA}$$

demonstrating that the use of two feeder cables to the substation *increases* the fault value.

The introduction of power transformers into the electrical system does not complicate the calculation. By way of example one of the remaining feeder circuits in Fig. 3-5 might well control a transformer of say 2 500 kVA rating as shown in Fig. 3-16 and it is required to determine the short-circuit value at a point just beyond the transformer for the purpose of selecting a circuit-breaker to install at this point. Using the reactance value of the transformer as given in Table 3 : 2, the impedance diagram for the system will be as shown in Fig. 3-17 which at once reduces to Fig. 3-18 by addition of series values, and the short-circuit MVA at the fault will be:—

$$\text{S.C. MVA} = \frac{10\,000}{293{\cdot}33} \qquad = 34{\cdot}1 \text{ MVA}$$

A very interesting method to illustrate the value of impedance diagrams and their reduction to a single final impedance value is one in which the use of busbar reactors is employed in order to reduce the fault MVA under short-circuit conditions.

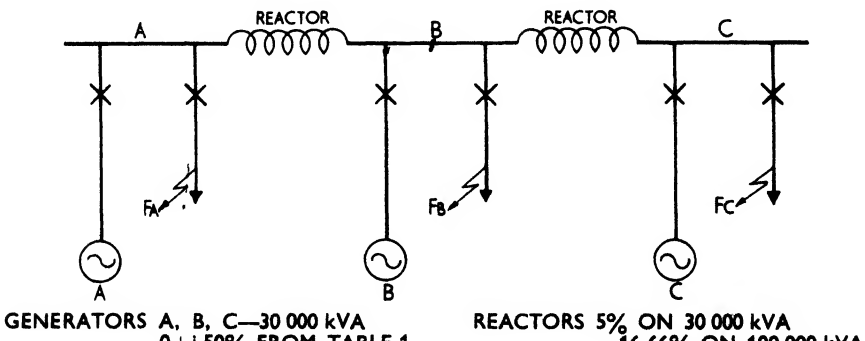


FIG. 3-19.

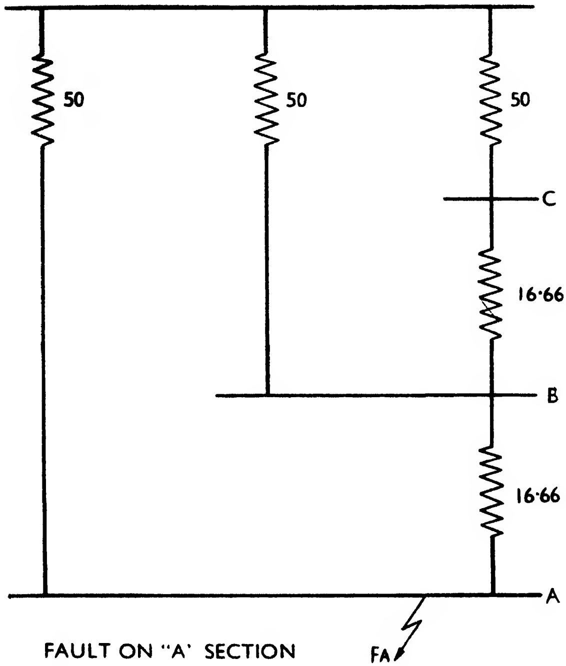


FIG 3-20. (a)

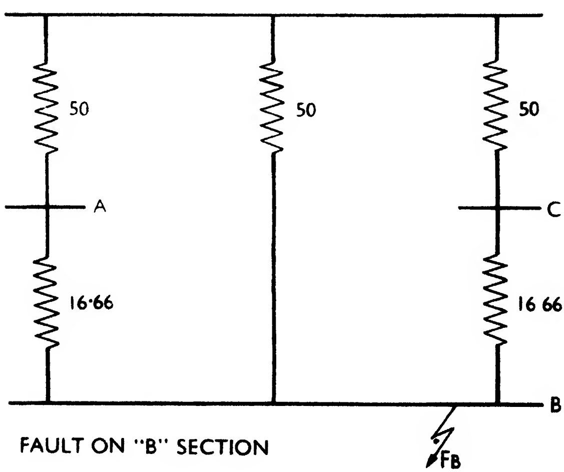
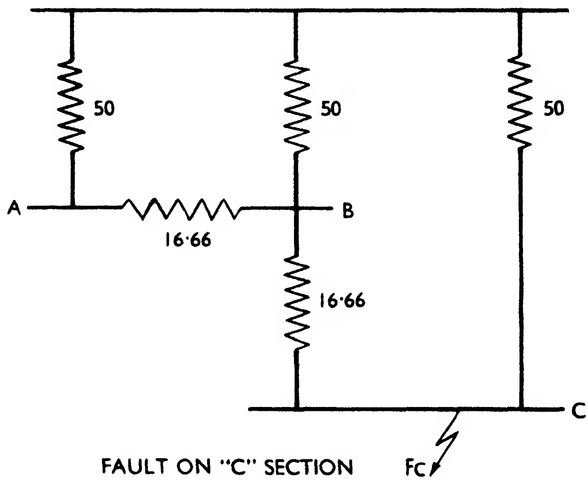


FIG. 3-20 (b)

Fig. 3-19 is typical of this arrangement and by calculations as previously demonstrated it can be shown that if the busbar reactors are omitted, the fault value with all three machines in operation would be of the order of 600 MVA. With reactors installed, the first step is to set down the diagram in impedance form for three fault conditions, namely for faults at the points F_A, F_B and F_C, and this has been done in Fig. 3-20. As in this example we are not concerned with resistance values, only the reactance figures are indicated.



FAULT ON "C" SECTION

Fig. 3-20 (c)

For a fault at F_A, the first step is to solve the parallel values 50, 50 and 16·66 to busbars B and C, as follows: -

$$\frac{1}{\frac{1}{50}+\frac{1}{50+16{\cdot}66}}$$

$$=\frac{1}{0{\cdot}02+0{\cdot}015} \qquad =28{\cdot}6\%$$

The diagram now reduces to Fig. 3-21 a study of which reveals a further parallel network solved as follows:—

$$\frac{1}{\frac{1}{50}+\frac{1}{28{\cdot}6+16{\cdot}66}}$$

$$=\frac{1}{0{\cdot}02+0{\cdot}022} \qquad =23{\cdot}8\%$$

which can be shown in the resultant diagram Fig. 3-22 and the short-circuit value for a fault at F_A will be:—

$$\text{S.C. MVA}=\frac{10\,000}{23{\cdot}8} \qquad =420 \text{ MVA}$$

For a fault at F_B we have a simple case of parallel values which can be reduced in one step to an equivalent as follows:—

$$\frac{1}{\frac{1}{50+16\cdot66}+\frac{1}{50}+\frac{1}{50+16\cdot66}}$$

$$= \frac{1}{0\cdot015+0\cdot02+0\cdot015} = 20\%$$

shown in diagram Fig. 3-23 and giving a short-circuit value of

$$\text{S.C. MVA} = \frac{10\,000}{20} = 500 \text{ MVA}$$

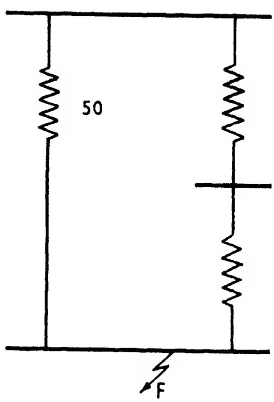


FIG. 3-21.

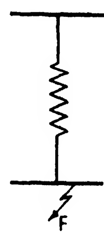


FIG. 3-22.

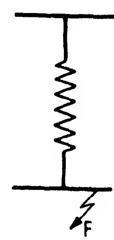


FIG. 3-23.

For a fault at F_C, this clearly will be the same as for F_A as we have a symmetrical system and the value will therefore be 420 MVA.

In addition to demonstrating the use of network reduction this example shows how the introduction of current limiting reactors results in a worthwhile reduction in fault values. This is not always an economical procedure and later in this chapter some notes will be included as to their use.

So far, the examples given have covered impedances in series and parallel branches. There are many instances where the impedances are connected either in star or in delta and in such cases network reduction is achieved

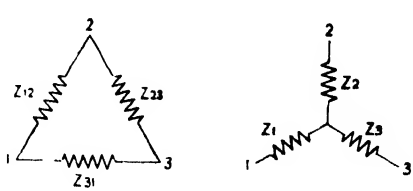


FIG. 3-24.

by the use of two three terminal transformations by means of which the three impedances connected in star may be replaced by an equivalent delta connected group or vice versa.

The delta/star transformation is the easiest manipulation and if the three values $Z12$, $Z23$ and $Z31$ as in Fig. 3-24 are known, the equivalent star values $Z1$, $Z2$ and $Z3$ can be determined from:—

$$Z1=\frac{Z12\ Z13}{Z12+Z23+Z31}$$

$$Z2=\frac{Z23\ Z12}{Z12+Z23+Z31}$$

$$Z3=\frac{Z31\ Z23}{Z12+Z23+Z31}$$

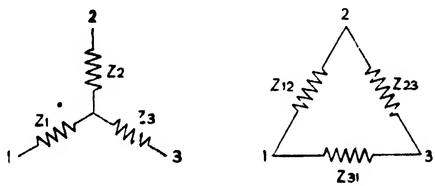


FIG. 3-25.

Alternatively, given the three values $Z1$, $Z2$ and $Z3$ in a star-connected group as Fig 3-25, the equivalent delta values are determined from:—

$$Z12=Z1+Z2+\frac{Z1\ Z2}{Z3}$$

$$Z23=Z2+Z3+\frac{Z2\ Z3}{Z1}$$

$$Z31=Z3+Z1+\frac{Z3\ Z1}{Z2}$$

To demonstrate the use of a delta/star transformation an electrical layout such as that shown in Fig. 3-26* may be used, where four generators are tied to a ring busbar with reactors in the busbars. In this diagram the values given are those on our chosen base of 100 000 kVA.

The fault is assumed to occur on the busbars at the point F. The calculations would apply equally for a fault on the adjacent feeder circuit at a point close up to the circuit-breaker.

The impedance diagram for the system is shown in Fig. 3-27 a study of which reveals two delta combinations comprising the impedances:—

75 : 65 : 100
100 : 80 : 100

**This example and the subsequent diagrams Figs. 3-27/3-35 inclusive are reproduced from "The Calculation of Faults Currents in Electrical Networks" by permission of the publishers, Sir Isaac Pitman and Sons Ltd. London.*

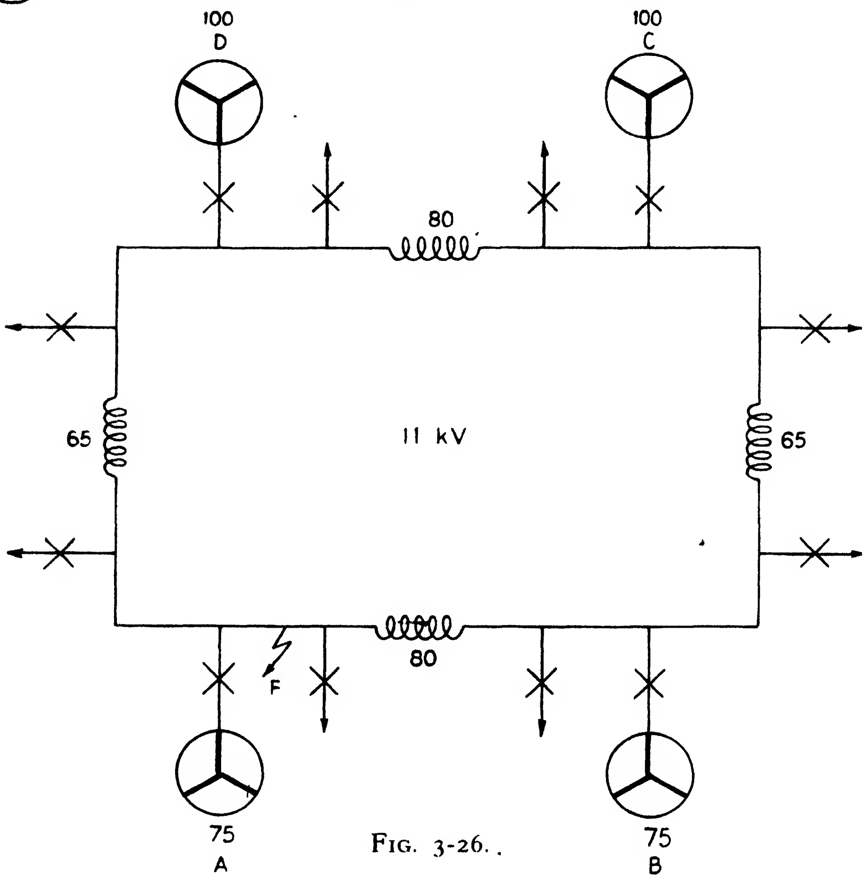


FIG. 3-26.

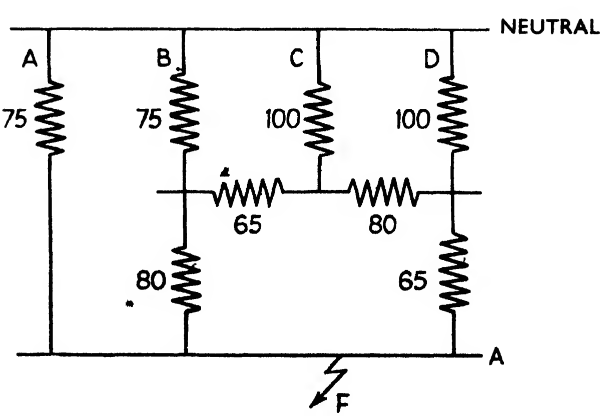


FIG. 3-27.

and the first step will be to convert one of these groups to a star formation, introduce it into a new diagram before converting the other group, the values of which will be revealed.

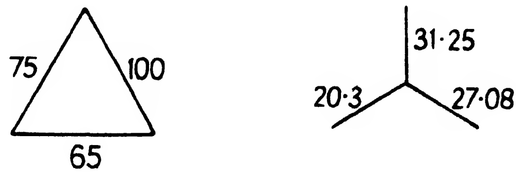


FIG 3-28.

Taking the first group 75, 65 and 100 the calculation, using the formula given, is:--

$$Z1 = \frac{75 \cdot 65}{75+100+65} \quad 20 \cdot 3$$

$$Z2 = \frac{100 \cdot 75}{75+100+65} \quad 31 \cdot 25$$

$$Z3 = \frac{65 \cdot 100}{75+100+65} \quad 27 \cdot 08$$

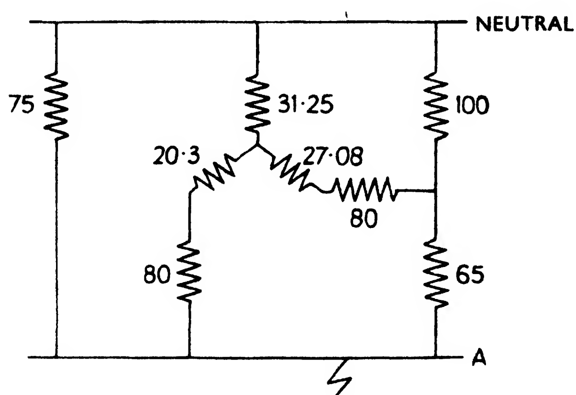
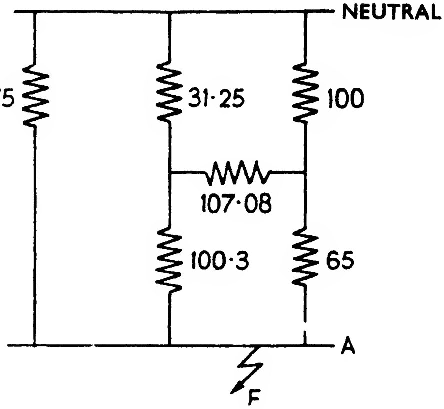


FIG 3-29.

The result of this calculation is shown in Fig. 3-28 and a new network diagram is now produced as in Fig. 3-29 in which the star formation has been introduced. In this diagram there are impedances in series, i.e. (20·3 and 80) and (27·08 and 80) and adding these arithmetically enables the impedance diagram to be reduced to Fig. 3-30.



• Fig 3-30

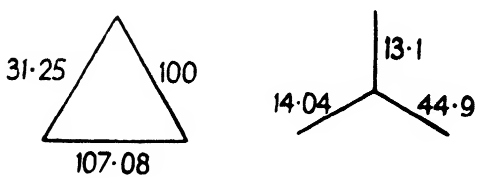


Fig. 3-31

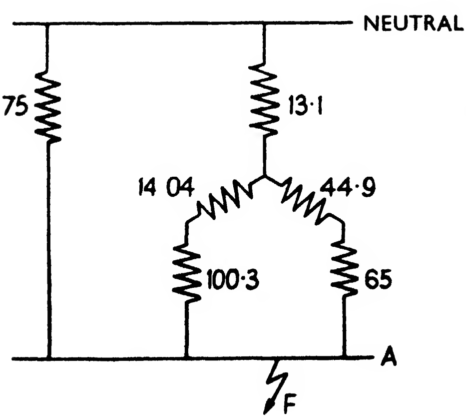


Fig. 3-32.

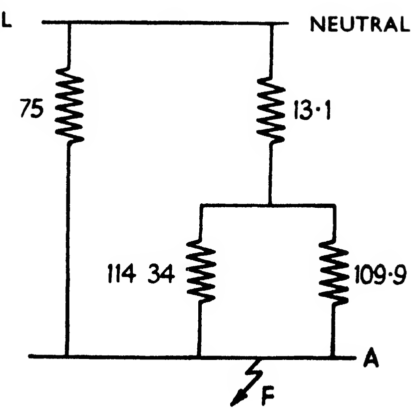


Fig. 3-33.

This reveals that the other delta group now comprises the values:

$$31\cdot25 : 107\cdot08 : 100$$

Calculating as before, the equivalent star group will be as shown in Fig. 3-31 and this is introduced in the network diagram as in Fig. 3-32. Adding the series values in this diagram results in Fig. 3-33 which shows two values 114·34 and 109·9 in parallel and the resultant of these is:—

$$\frac{1}{\frac{1}{114\cdot39}+\frac{1}{109\cdot9}}=56$$

leaving the network as shown in Fig. 3-34.

The parallel values now shown are again resolved thus:—

$$\frac{1}{\frac{1}{75}+\frac{1}{13\cdot1+56}}=35\cdot96$$

leaving a final impedance diagram as in Fig. 3-35 and the short-circuit value for a fault at F will be:—

$$\text{S.C. MVA } \frac{10\,000}{35\cdot96} = 278 \text{ MVA}$$

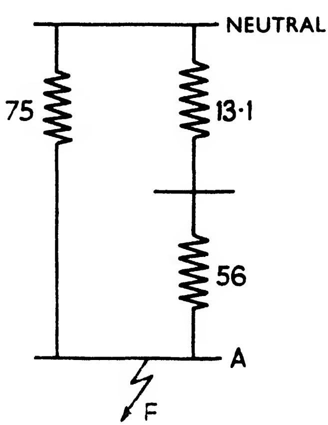


FIG. 3-34.

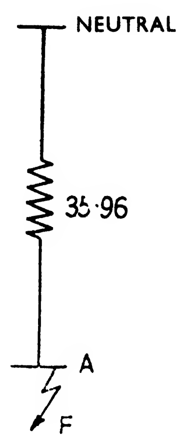


FIG. 3-35.

In the examples based on Figs. 3-8 and 3-12, transmission of power has been assumed to be by means of three-core cables for which reactance values have been given in Tables 3 : 3 and 3 : 4. In many instances, and

particularly in the higher voltage range 33-275 kV, transmission will be by means of overhead lines and while this will not modify the means by which calculations are made, no reasonably simple tables equivalent to those for cables can be given to cover all the possible variants of spacing and formation. An approximate formula to give the reactance per phase at 50 cycles per second is:

$$X = H + 0{\cdot}233 \log_{10} \left(\frac{D}{R}\right) \text{ ohms per mile.}$$

where H is a constant and D is the spacing between conductors when uniform.

When, in a three phase system, the conductors are not spaced at the corners of an equilateral triangle, D must be taken as

$$\sqrt[3]{abc}$$

where a, b and c are the spacings of each pair and R is the radius of cross-section of the conductors.

Dimensions D and R (and a, b, c, if used) must all be in the same units.

The constant H is taken as follows:

Solid conductors	0·0253
3 strand	0·0378
7 strand	0·0321
19 strand	0·0280
37 strand	0·0267
61 strand	0·0264

and from this it will be clear that innumerable tables would be necessary to cover every possibility.

Two authors have, however, offered a table of *average* figures which are sufficiently accurate for short-circuit calculations of the type with which we are concerned. Table 3 : 5 has been compiled on the basis of the figures given by these authors.*

"Rupturing Capacity and Plant Impedance" by E. A. Beavis "The Electrician" 12th August, 1940.
"The Calculation and Design of Electrical Apparatus" by W. Wilson, 2nd Edition 1940 Chapman and Hall Ltd.

Table 3 : 5

OVERHEAD COPPER CONDUCTORS.

Conductor size sq. in	Percentage resistance (R) and reactance (X) per yard on a 100 000 kVA base							
	3·3 kV		6·6 kV		11 kV		22 kV	
	R	X	R	X	R	X	R	X
0·05	0·454	0·321	0·113	0·080	0·041	0·029	0·010 2	0·007 5
0·10	0·227	0·301	0·057	0·075	0·020	0·027	0·005 1	0·007 1
0·15	0·152	0·291	0·038	0·073	0·014	0·026	0·003 4	0·006 9
0·20	0·113	0·283	0·028	0·071	0·010	0·025 5	0·002 5	0·006 7
0·25	0·091	0·277	0·023	0·069	0·008	0·025	0·002 1	0·006 6
0·30	0·075	0·269	0·019	0·067	0·007	0·024 2	0·001 7	0·006 4
0·40	0·057	0·261	0·014	0·065	0·005	0·023 6	0·001 3	0·006 2
0·50	0·046	0·257	0·012	0·065	0·004	0·023 1	0·001 0	0·006 1

Conductor size sq. in	33 kV		66 kV		132 kV		
	R	X	R	X	R	X	For aluminium conductors the resistance values increase by 60%. Values not seriously altered for steel cored lines.
0·05	0·004 5	0·003 3		—	—		
0·10	0·002 3	0·003 2	0·000 57	0·000 84	-	—	
0·15	0·001 5	0·003 1	0·000 38	0·000 81	0·000 095	0·000 22	
0·20	0·001 1	0·003 0	0·000 28	0·000 79	0·000 071	0·000 21	
0·25	0·000 9	0·002 9	0·000 23	0·000 78	0·000 057	0·000 21	
0·30	0·000 7	0·002 8	0·000 19	0·000 76	0·000 047	0·000 2	
0·40	0·000 6	0·002 7	0·000 14	0·000 74	0·000 036	0·000 2	
0·50	0·000 5	0·002 7	0·000 12	0·000 73	0·000 029	0·000 19	

Mention has already been made of the use of reactors as a means of introducing additional reactance for the purpose of reducing fault values.

This practice is usually adopted in order to take advantage of a standard switchgear rating or to protect older switchgear which has an inadequate rating when additional generating plant is added. In this discussion it is not intended to consider reactor design but only their use. It may however be noted that two types are in general use, namely an iron cored type and an air cored type.

The rating given to reactors is usually in percentage terms and, on a three phase system at 6 600 volts, a 20 per cent reactor is one which will have a voltage drop of 763 volts across it with full load current flowing, i.e. 20 per cent of line to neutral volts, in this case of 3 815 volts.

In general, reactors should be located at points in the network where they can be most effective. Very few occasions arise where it is necessary or desirable to add reactance in a generator circuit as modern machines have sufficient inherent reactance to enable them to withstand the forces

of short-circuit. If modern machines are to be paralleled with older ones, a case may arise where added reactance in the circuits of the older machines will give protection and give them roughly the same characteristics as the new machines.

Reactors installed in individual feeder circuits are not an economical proposition as often a considerable number of feeders are involved. A good case, however, can be that of a group feeder (see Fig. 13-9, Chapter XIII) where the added reactance is essential to protect a group of circuit-breakers of low breaking capacity. Similarly, an interconnector between new and old sections of an installation may profitably include a reactor and thus avoid the need to replace older circuit-breakers.

Feeder reactors have the advantage of localising the disturbance to the feeder on which trouble occurs, a point of importance where synchronous machines are in service. The usual value of reactance for feeder circuits is of the order of 3 to 5 per cent based on the normal current loading of the circuit. Here it should be noted that with loads of poor power factor, serious interference with regulation can arise but at or near to unity power factor the effect on regulation is negligible. This is indicated in Table 3 : 6 below.

TABLE 3 : 6

INCREASE IN REGULATION.

Added reactance percentage	1·0 p.f.	0·9 p.f.	0·8 p.f.	0·5 p.f.
1	—	0·4	0·5	0·75
2	—	0·75	1·15	1·5
3		1·25	1·75	2·4
4	0·1	1·6	2·4	3·25
5	0·15	2·2	3·0	4·1
6	0·2	2·7	3·75	5·0
7	0·25	3·2	4·5	6·0
8	0·3	3·75	5·15	7·0
9	0·4	4·3	5·8	8·0
10	0·5	5·0	6·6	9·0

It must be borne in mind too that added reactance also affects the power factor and this is demonstrated in Fig. 3-36.

The alternative location for reactors is in the busbar system and three typical methods are noted in Chapter XIII, Figs. 13-14, 13-15 and 13-16. These schemes give protection in the event of faults on the busbars, generators or feeders and if suitably chosen, trouble on one section will not disturb the voltage on adjacent sections due to current flow to the faulty section, but the reactors must permit the interchange of current to equalise the generator loadings. The current normally carried is generally small and the losses are not high nor is the regulation seriously affected. On the other hand,

there must be a difference in phase angle between busbar sections, a difference which may be appreciable between the extreme ends of a large installation.

The following example is included to show how the value of a busbar reactor may be determined. Fig. 3-37 shows an installation comprising to

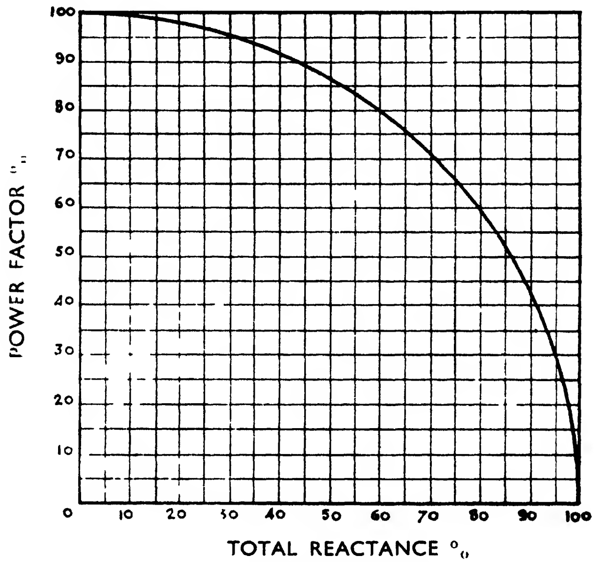


FIG. 3-36 *Effect of added reactance on power-factor*

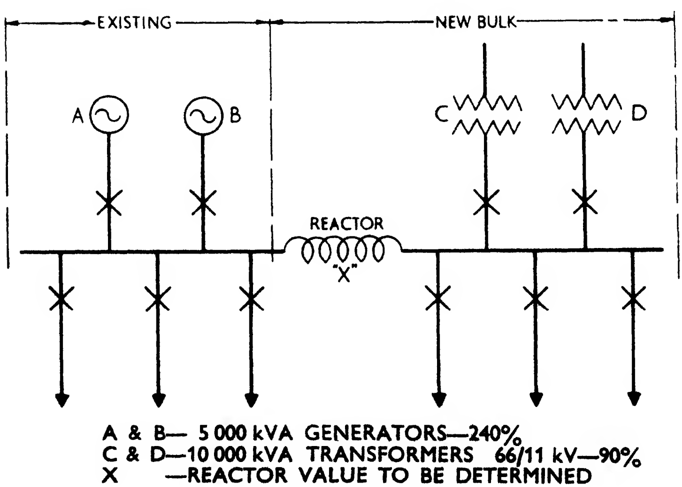


FIG. 3-37.

the left, an existing system of two 5 000 kVA generators with appropriate outgoing feeders. A simple calculation here will show that the fault value under the original circumstances would be 83·3 MVA and because of this switchgear rated at 100 MVA was installed.

It is now intended to take additional supplies in bulk, by way of two 10 000 kVA transformers and it is obvious that unless additional reactance is introduced between the new and the old plant, the breaking capacity of the existing switchgear will be far from adequate, as the two transformers can contribute a further 222 MVA. The value of this additional reactance may be calculated as follows, the calculations being on our 100 000 kVA base.

Total reactance necessary to safeguard existing switchgear

$$= \frac{100 . \text{kVA base}}{\text{MVA rating of switchgear} . 1\,000}$$

$$= \frac{100 . 100\,000}{100 . 1\,000} = 100\%$$

Reactance of existing machines in parallel

$$\frac{240}{2} = 120\%$$

Reactance of new transformers in parallel

$$\frac{90}{2} = 45\%$$

The value of X is calculated from

$$\frac{1}{120} + \frac{1}{45+X} = \frac{1}{100}$$

$$\frac{1}{45+X} = \frac{1}{100} - \frac{1}{120}$$

$$= \frac{6}{600} - \frac{5}{600} = \frac{1}{600}$$

i.e. $45+X = 600$

and $X = 555\%$ on a 100 000 kVA base

If it is assumed that the reactor rating is 5 000 kVA then X at this rating will be—

$$\frac{5\,000}{100\,000} . 555 = 27\% \text{ approx}$$

Up to this point our calculations have been concerned with systems at 3 300 volts or higher and it is necessary now to consider the equally important problem of fault values which arise on systems in the 400-600 volt range. Here the principles previously outlined do not vary but it is important to ensure that every factor contributing to impede the fault current be taken into account and more particularly the often considerable effect of cable connections. Too often it is thought that say, 31·0 MVA at 415 volts is an easy rating as compared, say, with 150 MVA at 6 600 volts or 250 MVA at 11 000 volts and in voltage terms perhaps this immediate thought is justified.

If, however, these MVA values are converted to current, a different picture emerges as it is then found that 150 MVA at 6 600 volts and 250 MVA at 11 000 volts are each equivalent to a symmetrical r.m.s. current 13 100 amperes whereas 31 MVA at 415 volts is equivalent to

43 300 amperes. These, then, are the values that the circuit-breakers on the respective systems must be capable of "breaking". On "making", however, the current values may be from 2 to 2·55 times as great, depending upon power factor. These latter currents are known as the initial peak currents which occur in the first half-cycle of short-circuit and the switchgear designer is concerned not only with the interrupting ability of the circuit-breaker but also with the electromagnetic and thermal stresses on busbars, connections and other apparatus, caused by such heavy currents.

This brief comment, therefore, emphasises the need for reasonably accurate assessments of fault values at the lower voltages* if only for economic reasons. Later in the chapter it will be shown how important it is in relation to the cables connected to l.v. switchgear bearing in mind that these have also to carry the current, withstand the electromagnetic forces and keep within safe temperature limits.

It is always possible to arrive at a maximum fault value by taking the transformer kVA rating and its reactance or impedances and calculating from the simple formula:—

$$\text{S.C. MVA} = \frac{\text{transformer kVA} \cdot 100}{\text{percentage reactance} \cdot 1\,000}$$

and unfortunately this is often the practice adopted to arrive at a rating to include in a switchgear purchasing specification and results regularly in a tender for gear of higher rating than can be justified by facts, and of course more costly. The use of this formula can only be accurate for a fault right at the transformer secondary terminals and only then if a solidly bolted short-circuit can be envisaged, a condition which can be produced, or nearly so, in a short-circuit test plant but most improbable in service. If there are two or more transformers in parallel then it becomes an impossibility. However, it is interesting at this stage to see what MVA values may be calculated by this means and Table 3 : 7, below, is designed to show these for a range of transformers which are normally used at main l.v. supply points to industrial or domestic users, where the primary voltage does not exceed 11 000 volts.

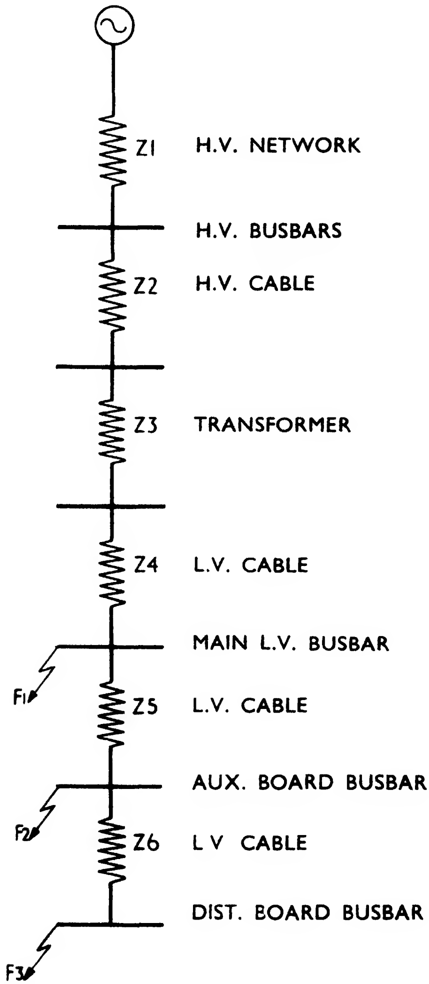
TABLE 3 : 7

FAULT VALUES AT TRANSFORMER TERMINALS.

Single transformer		Two transformers in parallel		Three transformers in parallel		Four transformers in parallel	
kVA	S.C. MVA	kVA	S.C. MVA	kVA	S.C. MVA	kVA	S.C. MVA
400	8·42	—	—	—	—	—	—
500	10·5	—	—	—	—	—	—
750	15·8	2×400	16·8	—	—	—	—
1 000	21·0	2×500	21·0	3×400	25·26	—	—
1 250	25·0	2×750	31·4	3×400	25·26	4×400	33·7
1 500	27·3	2×750	31·4	3×500	31·5	4×400	33·7
2 000	33·33	2×1 000	42·0	3×750	47·4	4×500	42·0

**This presentation of l.v. short-circuit calculations follows a pattern devised by the author in a book written by him for The Belmos Co. Ltd. (see bibliography). The Tables 3:7 to 3:12 and some of the worked examples are similar except that a base of 100 000 kVA has been used instead of 10 000 kVA. This source is gratefully acknowledged.*

Because the loss of one transformer out of a bank is not so wide-ranging in its effects as would be the loss of a single large unit; because of the operational flexibility afforded, and because of the lower normal currents to be carried by both switchgear and cables, many engineers prefer to use several transformers in parallel but in so doing, it should be noted that in some instances the short-circuit MVA will be higher for an equal *total* kVA capacity. Thus is shown in Table 3 : 7 where, for example, one



FAULT AT F1 LIMITED BY IMPEDANCES Z1 Z2 Z3 Z4
FAULT AT F2 LIMITED BY IMPEDANCES Z1 Z2 Z3 Z4 Z5
FAULT AT F3 LIMITED BY IMPEDANCES Z1 Z2 Z3 Z4 Z5 Z6

FIG. 3-38.

2 000 kVA transformer results in 33·33 MVA whereas if four 500 kVA transformers are used, the result is 42 MVA. Where transformers in parallel are used and high short-circuit values result, sectionalised busbars should always be resorted to and the normal operating condition would be to run with the sectionalising switch open, effectively dividing the system into two (or more) parts with consequent reduction in MVA values on each section. A later example will demonstrate this point.

Based on Table 3 : 7 it is noted that if calculations are made on the basis of the transformer reactance alone, then a single 1 000 kVA transformer would dictate the need for 25 MVA switchgear and a single 2 000 kVA transformer would call for 35 MVA. But on medium voltage systems, this may well be unrealistic as there are often several other impedances in circuit which must tend to reduce the fault value. What these other impedances are will be clear from Fig. 3-38, and we can now proceed to tabulate these in preparation for some worked examples.

H.V. NETWORK

The earlier part of this chapter has been devoted to demonstrating the methods by which the impedance or reactance of the h.v. network can be deduced and from this, the fault value at the h.v. busbars. This impedance or reactance figure may be used in l.v. calculations or if it is not known exactly, the MVA rating of the h.v. switchgear may be used in the following formula to give the equivalent percentage reactance of the h.v. network.

$$\text{Equivalent percentage reactance of h.v. network} = \frac{\text{base kVA} \cdot 100}{\text{known MVA* at h.v. busbars} \cdot 1\,000}$$

*(or MVA rating of h.v. switchgear).

Base kVA in our calculations has been fixed at 100 000 kVA and on this basis, Table 3 : 8 is compiled for later use.

TABLE 3 : 8

Known calculated MVA or breaking capacity rating of h.v. switchgear	Equivalent percentage reactance of h.v. network on a 100 000 kVA base
50*	200
75*	133·3
100*	100·0
125	80·0
150*	66·6
175	57·0
200	50·0
250*	40·0
300	33·33
350*	28·7
400	25·0
450	22·22
500*	20·0

*MVA values marked * are standard h.v. switchgear ratings.*

If the calculated MVA at the h.v. busbars is known, the figure in Table 3 : 8 nearest above should be used, e.g. if calculations give 278 MVA, use 300 MVA in the table. This gives a small margin of safety.

TRANSFORMERS. These have been dealt with earlier and Table 3 : 2 is applicable in what follows.

CABLES (H.V.) Similarly, high voltage cables as given in Tables 3 : 3 and 3 : 4 can be applied in the appropriate calculations for lower voltages.

CABLES (L.V.) Percentage reactance tables for multicore cables can readily be calculated from manufacturers tables giving ohmic values using the formula noted on page 20 and Table 3 : 9 results, still using the selected base of 100 000 kVA, and in values *per yard*.

When the larger transformers noted in Table 3 : 7 are employed, the normal current on the secondary side is comparatively high and the use of single core cables, often several in parallel per phase, is preferred as against the use of large three core cables.

TABLE 3 : 9

L.V. PAPER CABLES, 3 OR 4-CORE 1 100 V, 50 C/S TO B.S.480 : 1954

Cable size sq. in.	Percentage resistance and reactance per yard on a 100 000 kVA base											
	400 V		415 V		440 V		500 V		550 V		600 V	
	R	X	R	X	R	X	R	X	R	X	R	X
0·007	222	5·53	207	5·13	184	4·57	143	3·54	118	2·95	99	2·46
0·014 5	107	5·05	98·6	4·7	88	4·18	68	3·24	51	2·69	47	2·25
0·022 5	70·5	4·83	65·3	4·5	58	4·00	45	3·10	37·6	2·58	31	2·15
0·04	40·0	4·42	37·5	4·06	32·5	3·66	25·2	2·80	21·1	2·36	17·5	1·96
0·06	26·0	4·27	24·1	3·97	21·5	3·53	16·6	2·74	13·9	2·28	11·6	1·90
0·10	15·5	4·11	14·5	3·83	12·8	3·4	10·0	2·64	8·2	2·19	6·8	1·83
0·15	10·6	3·97	9·8	3·70	8·6	3·28	6·76	2·54	5·6	2·12	4·7	1·76
0·20	8·0	3·92	7·4	3·92	6·6	3·25	5·1	2·51	4·34	2·09	3·5	1·74
0·25	6·4	3·90	5·8	3·63	5·2	3·23	4·0	2·50	3·37	2·08	2·8	1·73
0·30	5·3	3·88	4·9	3·60	4·4	3·21	3·4	2·48	2·82	2·07	2·35	1·72
0·40	4·0	3·85	3·7	3·57	3·3	3·18	2·56	2·46	2·14	2·06	1·8	1·71
0·50	3·4	3·81	3·1	3·53	2·76	3·15	2·13	2·44	1·78	2·04	1·5	1·69
0·60	2·83	3·76	2·6	3·48	2·33	3·10	1·8	2·40	1·51	2·04	1·26	1·67
0·75	2·4	3·76	2·2	3·48	2·0	3·10	1·53	2·40	1·30	2·01	1·10	1·67
1·00	1·9	3·70	1·8	3·45	1·58	3·08	1·22	2·38	1·02	1·98	0·85	1·65

NOTES: (1) *Allowances made for lay.*
(2) *Resistance values based on a temperature of 20°C (68°F).*

To determine the reactance of such cables is a matter of some complication, the calculations necessary requiring a knowledge of spacing, sheath currents, how laid (i.e. in magnetic or non-magnetic ducts or in free air), together with other factors. The variables are therefore many, particularly in the matter of spacing and formation where the possibilities are

almost unlimited. Some of the possible formations are noted in Fig. 3-39 and assuming space is available it will be clear that the spacing "S" can be varied at will and indeed, as the reactance increases as the spacing is increased, this offers a means whereby additional reactance is obtained to assist in MVA reduction. The problem is further complicated where, as

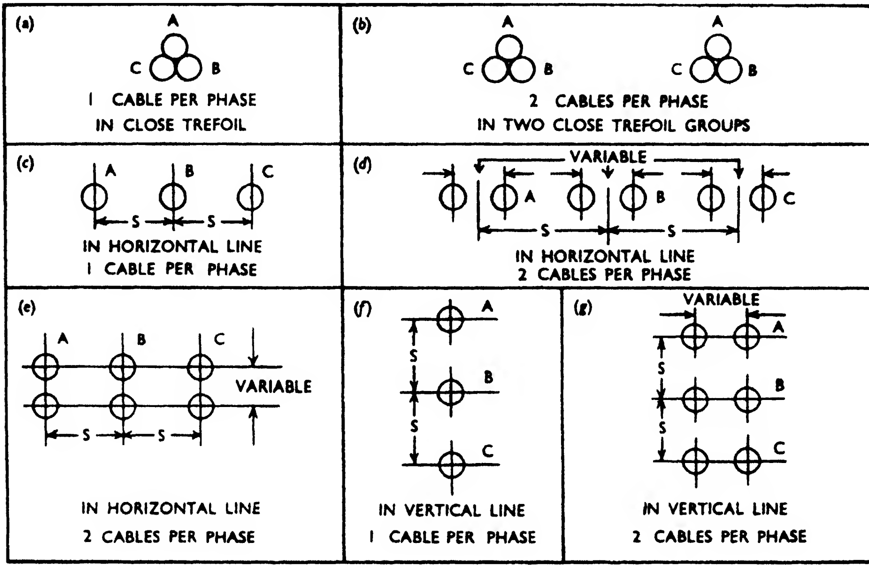


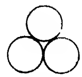
FIG. 3-39.—*Showing a few of the possible formations for single-core cables. Heavy currents may demand three such cables per phase.*

at (d), (e) and (g) in Fig. 3-39 there is more than one cable per phase which again may be on variable centres. In such cases a complex calculation is involved in which the multiple conductors per phase are first of all reduced to a single cable equivalent.

It is for reasons such as these that reference books rarely give reactance tables for single core cables in the manner given for multicore types as it is manifestly impossible to do so for all possible variations. The simplest arrangements are those in Fig. 3-39 at (a), (c) and (f), i.e. one cable per phase, and Tables 3 : 10 and 3 : 11 have been compiled to cover these within narrow limits. The tables, for example, cover only the largest cable sizes as being those used most regularly in practice. No values of resistance have been given as these are so much smaller than the reactance values that they can be ignored in fault calculations and regarded as a small factor of safety.

Should the need arise to include in any calculation the reactance value for other formations or spacings, or where more than one single core cable is used per phase, it is recommended that the appropriate data be sought from the cable supplier.

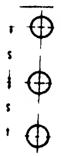
Table 3 : 10



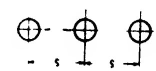
L V PAPFR LEAD SINGLE CORE CABLES UP TO 600 V 50 C/S LAID IN CLOSE TREFOIL, CABLES TOUCHING AND ONE PER PHASE

Cable size sq. in	Reactance in percentage per yard on a 100 000 kVA base					
	400 V	515 V	440 V	500 V	550 V	600 V
0·4	4·75	4·41	3·91	3·04	2·50	2·10
0·5	4·65	4·32	3·83	2·98	2·46	2·08
0·6	4·56	4·23	3·76	2·92	2·41	2·04
0·75	4·51	4·18	3·71	2·88	2·38	2·02
1·0	4·43	3·83	3·65	2·84	2·34	1·99

Table 3 : 11



L V. PAPER LEAD SINGLE CORE CABLES UP TO 600 V 50 C/S—ONE CABLE PER PHASE RUN IN SINGLE LINE HORIZONTALLY OR VERTICALLY AS SHOWN



Phase spacing "S" in	Cable size sq in	Reactance in percentage per yard on a 100 000 kVA base					
		440 V	415 V	440 V	500 V	550 V	600 V
2	0·4	6·87	6·38	5·66	4·40	3·63	3·08
3		8·31	7·71	6·85	5·32	4·39	3·72
4		9·25	8·58	7·62	5·92	4·88	4·14
5		10·12	9·39	8·34	6·48	5·34	4·53
6		10·68	9·91	8·80	6·84	5·64	4·78
2	0·5	6·56	6·09	5·40	4·20	3·47	2·94
3		7·93	7·35	6·54	5·08	4·19	3·56
4		9·00	8·34	7·40	5·76	4·75	4·02
5		9·75	9·05	8·05	6·24	5·15	4·36
6		10·31	9·55	8·50	6·60	5·45	4·62
2	0·6	6·24	5·80	5·15	4·00	3·30	2·80
3		7·36	6·94	6·08	4·72	3·88	3·30
4		8·55	7·94	7·05	5·48	4·52	3·84
5		9·38	8·70	7·74	6·00	4·95	4·20
6		10·00	9·28	8·24	6·40	5·27	4·47
2	0·75	5·94	5·51	4·90	3·60	3·14	2·66
3		7·36	6·84	6·06	4·72	3·89	3·30
4		8·24	7·65	6·80	5·28	4·36	3·70
5		9·05	8·40	7·45	5·80	4·78	4·06
6		9·68	9·00	7·98	6·20	5·12	4·34
8		10·70	9·91	8·80	6·84	5·64	4·79
3	1·00	6·63	6·15	5·46	4·24	3·50	2·95
4		7·70	7·12	6·34	4·92	4·16	3·44
5		8·84	7·84	6·95	5·40	4·45	3·78
6		9·05	8·40	7·47	5·80	4·78	4·06
8		9·86	9·15	8·14	6·32	5·21	4·43

Bare copper conductors. As an alternative to the use of single core cables in heavy current applications, and particularly where the transformer is immediately adjacent to the l.v. switchgear with perhaps only a fire wall intervening, it is often convenient to do away with cables and all the joints they involve and use bare copper conductors in the form of busbars to join the transformer to the switchgear.

Here, as with single core cables, the values of reactance depend on spacing and formation and, in addition, on the cross-section and number of bars per phase. The detailed calculations are laborious and are outside the scope of this book but the interested readers requiring detailed information cannot do better than refer to a book published by the Copper Development Association entitled "Copper for Busbars" and to the many books or papers listed in the bibliography section of that book.

Here, making a few assumptions which make for simplification, Table 3 : 12 has been included to give percentage reactance per yard run on our selected base for various busbar sections at a number of phase spacings. The errors which the assumptions introduce are such as to be on the safe side for the purpose of short-circuit calculations. As with single core cables, resistance values can be ignored as they are small compared with reactance.

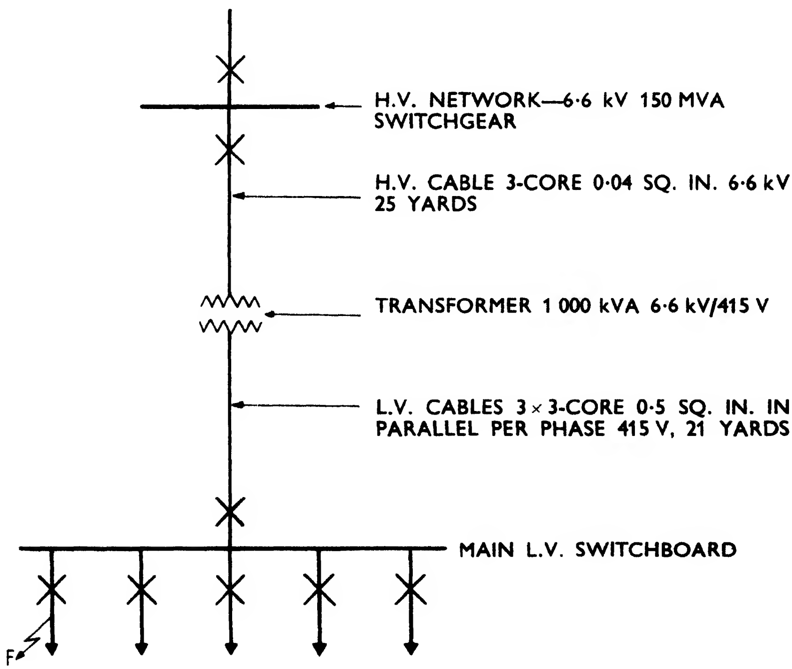
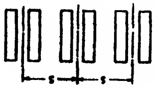


FIG. 3-40.

As a first example to demonstrate the use of the tables for calculating fault values at low voltages the simple system noted in Fig. 3-40, may be considered

TABLE 3 : 12



BARE COPPER CONDUCTORS (3-PHASE 50 C/S) PERCENTAGE REACTANCE PER YARD ON A 100 000 KVA BASE

No of bars	Section of each bar in.	Phase centres "S" in.	400 V	415 V	440 V	500 V	550 V	600 V	A.C. current rating in air based on 50°C rise on 35°C ambient temp amps
3	2 × ¼	4	7·1	6·4	5·7	4·4	3·3	3·1	2 175
		5	7·8	7·0	6·4	4·8	3·7	3·4	
		6	8·5	7·8	6·9	5·4	4·0	3·7	
		7	9·1	8·3	7·4	5·7	4·3	4·0	
		8	9·6	8·7	7·8	6·0	4·5	4·2	
		9	10·0	9·1	8·1	6·3	4·7	4·4	
2	3 × ¼	3	5·5	5·1	4·5	3·5	2·7	2·4	2 150
		4	6·5	5·9	5·3	4·1	3·1	2·9	
		5	7·3	6·7	6·1	4·6	3·5	3·2	
		6	8·0	7·3	6·5	5·0	3·8	3·5	
		7	8·6	7·8	7·0	5·4	4·1	3·7	
		8	9·0	8·3	7·4	5·7	4·3	3·9	
3	3 × ¼	4	6·1	5·5	4·9	3·8	2·9	2·7	2 750
		5	6·9	6·2	5·6	4·3	3·2	3·0	
		6	7·5	6·9	6·2	4·8	3·6	3·3	
		7	8·1	7·4	6·6	5·1	3·9	3·6	
		8	8·6	7·8	7·0	5·4	4·1	3·7	
		9	9·0	8·3	7·3	5·7	4·3	3·9	
4	3 × ¼	5	6·4	5·9	5·2	4·1	3·0	2·8	3 100
		6	7·1	6·5	5·8	4·5	3·4	3·1	
		7	7·7	7·1	6·3	4·9	3·7	3·4	
		8	8·2	7·5	6·7	5·2	3·9	3·6	
		9	8·6	7·8	7·0	5·4	4·1	3·8	
		10	9·0	8·3	7·3	5·7	4·3	4·0	
1	4 × ¼	3	5·2	4·8	4·3	3·3	2·6	2·3	1 475
		4	6·1	5·5	4·9	3·8	2·9	2·7	
		5	6·9	6·2	5·6	4·3	3·2	3·0	
		6	7·5	7·0	6·2	4·8	3·6	3·3	
		7	8·1	7·4	6·6	5·1	3·9	3·6	
		8	8·6	7·8	7·0	5·4	4·1	3·7	
		9	9·0	8·3	7·3	5·7	4·3	3·9	
2	4 × ¼	3	4·9	4·5	4·0	3·1	2·3	2·1	2 490
		4	5·7	5·2	4·6	3·6	2·7	2·5	
		5	6·4	5·9	5·2	4·1	3·0	2·8	
		6	7·1	6·5	5·8	4·5	3·4	3·1	
		7	7·7	7·1	6·3	4·9	3·7	3·4	
		8	8·2	7·5	6·7	5·2	3·9	3·6	
		9	8·6	7·7	7·0	5·4	4·1	3·8	
3	4 × ¼	5	6·2	5·7	5·1	3·9	3·0	2·7	3 080
		6	6·8	6·3	5·5	4·3	3·2	3·0	
		7	7·4	6·7	6·1	4·6	3·4	3·2	
		8	7·8	7·1	6·4	4·9	3·6	3·4	
		9	8·2	7·5	6·7	5·2	3·9	3·6	
		10	8·6	8·0	7·0	5·5	4·1	3·8	
		11	9·0	8·3	7·4	5·7	4·3	4·0	
		12	9·3	8·5	7·6	5·9	4·5	4·1	
4	4 × ¼	6	6·3	5·9	5·2	4·1	3·0	2·8	3 390
		7	7·0	6·4	5·7	4·4	3·3	3·1	
		8	7·5	6·8	6·1	4·7	3·6	3·3	
		9	7·9	7·1	6·5	4·9	3·8	3·5	
		10	8·3	7·5	6·8	5·2	4·0	3·7	
		12	8·9	8·3	7·3	5·7	4·2	3·9	
		15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

Following the procedure adopted for h v calculations this system can be redrawn as an impedance, diagram Fig 3-41, noting how the impedance values have been set out against each item and from which table they are

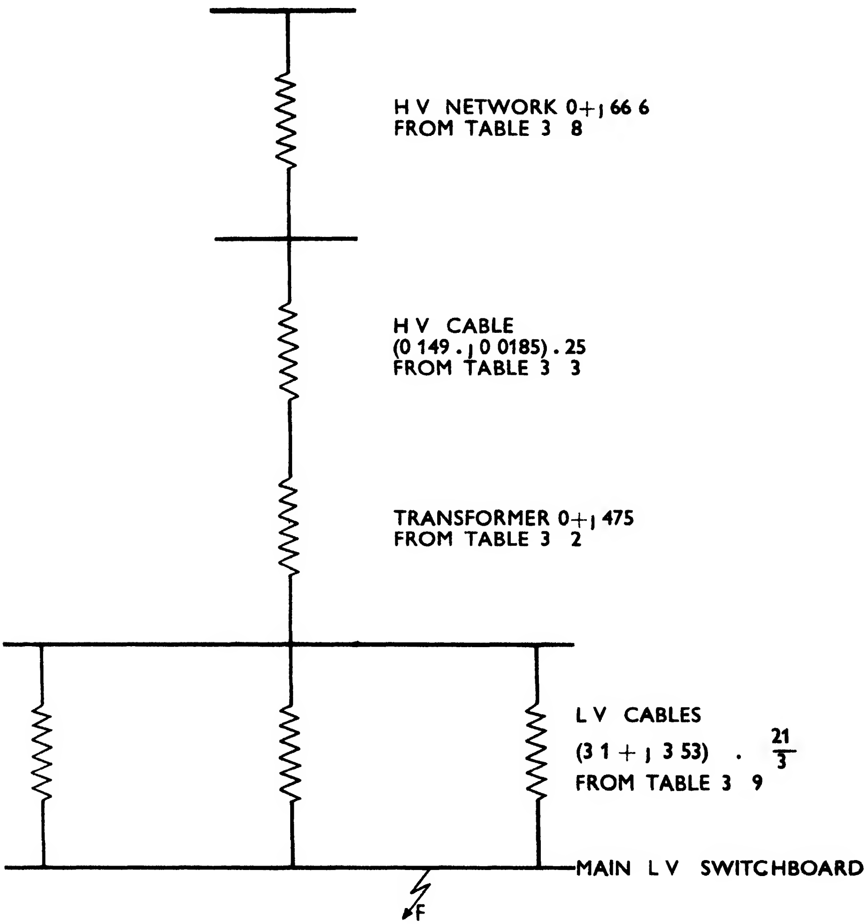


Fig 3 41

taken Note also that the multiplier 25 against the value for the h v cable is the length in yards, while the multiplier against the value for l v cable, 21/3, is the length divided by 3 on account of the three cables in parallel

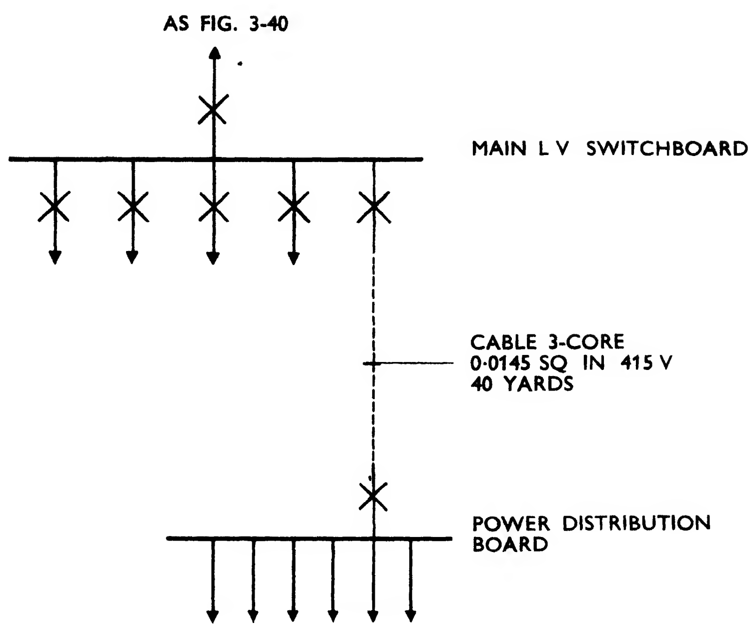


FIG 3-42

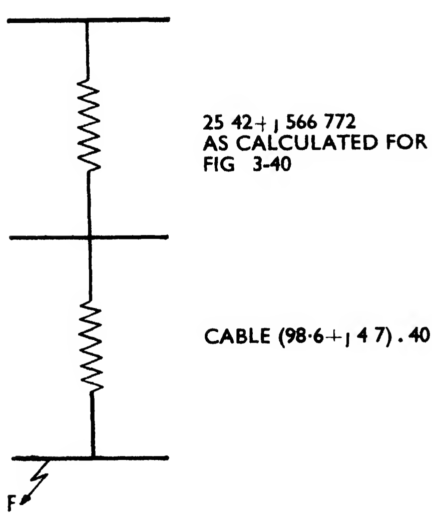


FIG 3-43.

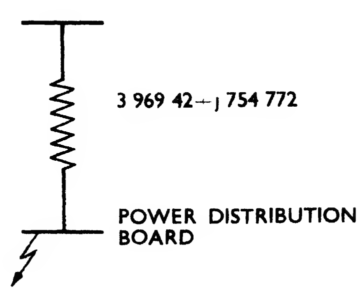


FIG. 3-44

The calculation proceeds by simply adding the impedance values (all in series) thus:—

H.V. network	=	$0 + j\,66{\cdot}6$
H.V. cable	=	$3{\cdot}72 + j\,0{\cdot}462$
Transformer	=	$0 + j\,475{\cdot}0$
L.V. cables	=	$21{\cdot}70 + j\,24{\cdot}71$
Z (Total)	=	$25{\cdot}42 + j\,566{\cdot}772$
	=	$\sqrt{25{\cdot}42^2 + 566{\cdot}772^2}$
	=	$567{\cdot}3\%$

and the short-circuit value for a fault at the busbars of the l.v. switchboard or on one of the outgoing feeders at a point close up to the circuit-breaker as at F in Fig. 3-40 is:—

$$\text{S.C. MVA} = \frac{10\,000}{567{\cdot}3} = 17{\cdot}63 \text{ MVA}$$

$$\text{P.F. at fault} = \frac{R}{Z} = \frac{25{\cdot}42}{567{\cdot}3} = 0{\cdot}0448$$

This calculation illustrates several points of interest:—

(a) That instead of 21·0 MVA as shown in Table 3 : 7 for a calculation based solely on the transformer impedance, we have the lower value of 17·63 MVA by including other factors, a reduction of some 15 per cent.

(b) That the inclusion of the h.v. cable has affected this result to a very small degree only.

(c) That the inclusion of the l.v. cables has had some effect if not large.

As a second example it is convenient to extend the one just considered by assuming that it is required to ascertain the fault value at a power distribution board fed from the main l.v. switchboard, generally as shown in Fig. 3-42. The impedance diagram for this can be set down as in Fig. 3-43 which reduces at once to Fig. 3-44 by adding the series impedances, and the calculation proceeds as follows:—

$$Z = 3\,969{\cdot}42 + j\,754{\cdot}772$$
$$= \sqrt{3\,969{\cdot}42^2 + 754{\cdot}772^2}$$
$$= 4041\%$$

and the short-circuit value for a fault at the distribution board is:—

$$\text{S.C. MVA} = \frac{10\,000}{4041} = 2{\cdot}475 \text{ MVA}$$

A study of this example shows the importance of the length of cable between main and distribution boards and how the resistance of the relatively small cable plays a preponderant part, being more than five times the reactance. The power factor at this point of fault will be

$$\text{P.F.} = \frac{R}{Z} = \frac{3\,969{\cdot}42}{4\,041} = 0{\cdot}982$$

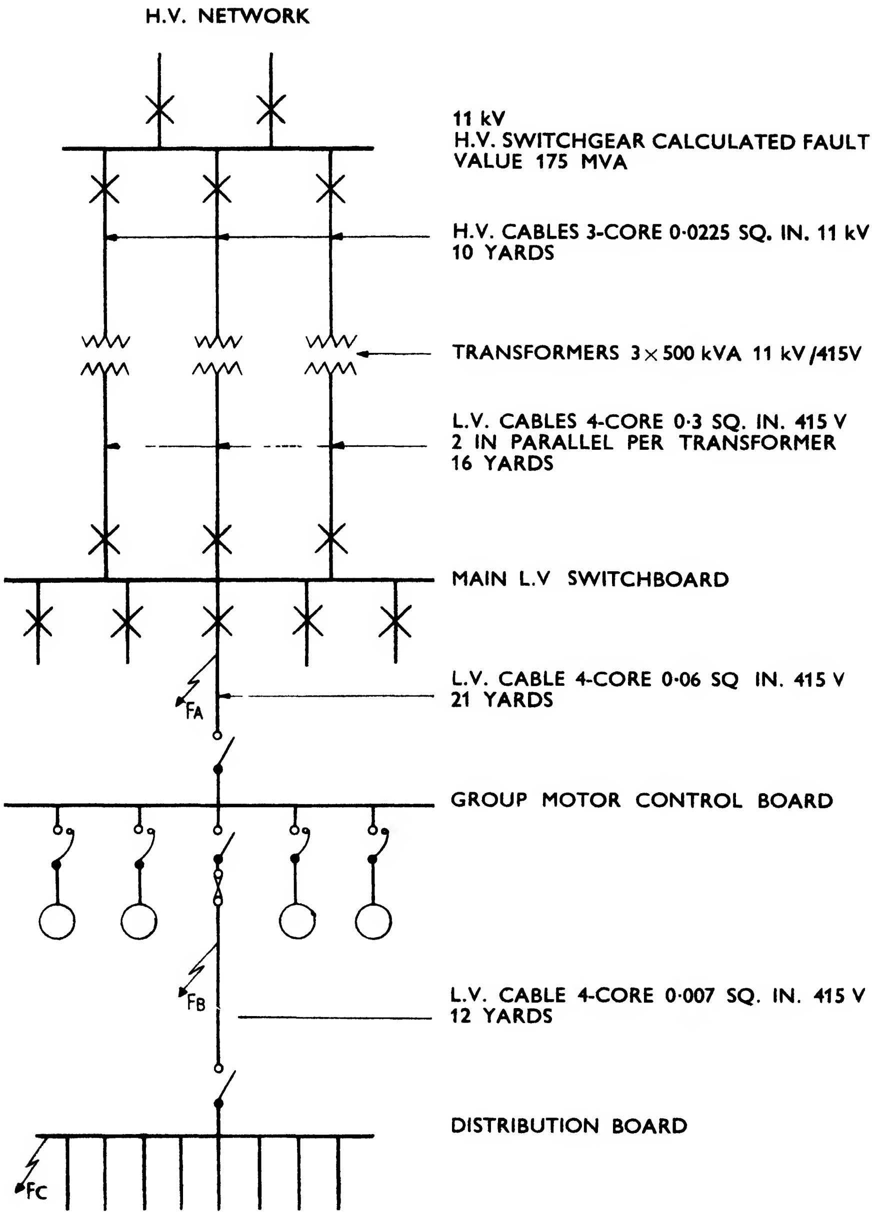

H.V. NETWORK
11 kV
H.V. SWITCHGEAR CALCULATED FAULT VALUE 175 MVA
H.V. CABLES 3-CORE 0·0225 SQ. IN. 11 kV 10 YARDS
TRANSFORMERS 3×500 kVA 11 kV/415V
L.V. CABLES 4-CORE 0·3 SQ. IN. 415 V 2 IN PARALLEL PER TRANSFORMER 16 YARDS
MAIN L.V SWITCHBOARD
L.V. CABLE 4-CORE 0·06 SQ IN. 415 V 21 YARDS
FA
GROUP MOTOR CONTROL BOARD
FB
L.V. CABLE 4-CORE 0·007 SQ. IN. 415 V 12 YARDS
DISTRIBUTION BOARD
FC

FIG. 3-45.

showing that where resistance is appreciable, the power factor will approach unity and the severity of fault clearance will be greatly eased.

It is appropriate now to consider the system in Fig. 3-45 when three transformers in parallel are used to give supply to a main l.v. switchboard, which in turn feeds a group motor control board and the latter in turn a sub-distribution board. It will be our purpose to ascertain the fault MVA at three points marked F_A, F_B and F_C. Translating to an impedance diagram we get Fig. 3-46 and the first step in a calculation of this type is to convert the impedances of the parallel cables between each transformer and the main l.v. switchboard into single equivalents and this reduces the impedance diagram to Fig. 3-47 down to the main switchboard (the continuing circuits omitted for convenience at this stage).

This leaves three parallel circuits which can be reduced by the simple process of dividing by three as each circuit is equal and the result is shown in Fig. 3-48. This shows a simple series arrangement and the impedances can be added arithmetically thus:—

H.V. network	0	+	j 57·0
H.V. cables	0·316	+	j 0·028
Transformers	0	+	j 316·0
L V cables	13·05	+	j 9·6
Z (Total) =	13·366	+	j 382·628

It is at once obvious that the reactance value is so large in comparison with resistance that for all practical purposes the latter may be ignored and the short-circuit value for a fault at or near to the main l.v. switchboard, as at F_A, will be

$$\text{S.C. MVA} = \frac{10\,000}{382{\cdot}628} = 26{\cdot}14 \text{ MVA}$$

If we look back to Table 3 : 7 it is noted that if the short-circuit value had been calculated on the basis of the transformers alone, the value would have been 31·5 MVA so that by taking into account other factors the value has been reduced by just over 20 per cent and unless further plant capacity is anticipated it would be satisfactory to install gear of 26 MVA rating instead of 31·0 or perhaps 35 MVA.

To calculate for a fault at the group motor control board (indicated F_B) the impedance diagram can be drawn as in Fig. 3-49 and adding for a series circuit we get:—

Impedance to main board	= 13·366	+	j 382·628
Cable	=506·4	+	j 83·37
Z (Total)	=519·776	+	j 465·998
	$=\sqrt{519^2+466^2}$		=698%

and the short-circuit value for a fault at point F_B will be:—

$$\text{S.C. MVA} = \frac{10\,000}{698} = 14{\cdot}33 \text{ MVA}$$

At this point it is worthy of note that the cable between the main l.v. switchboard and the group motor control board has effectively reduced

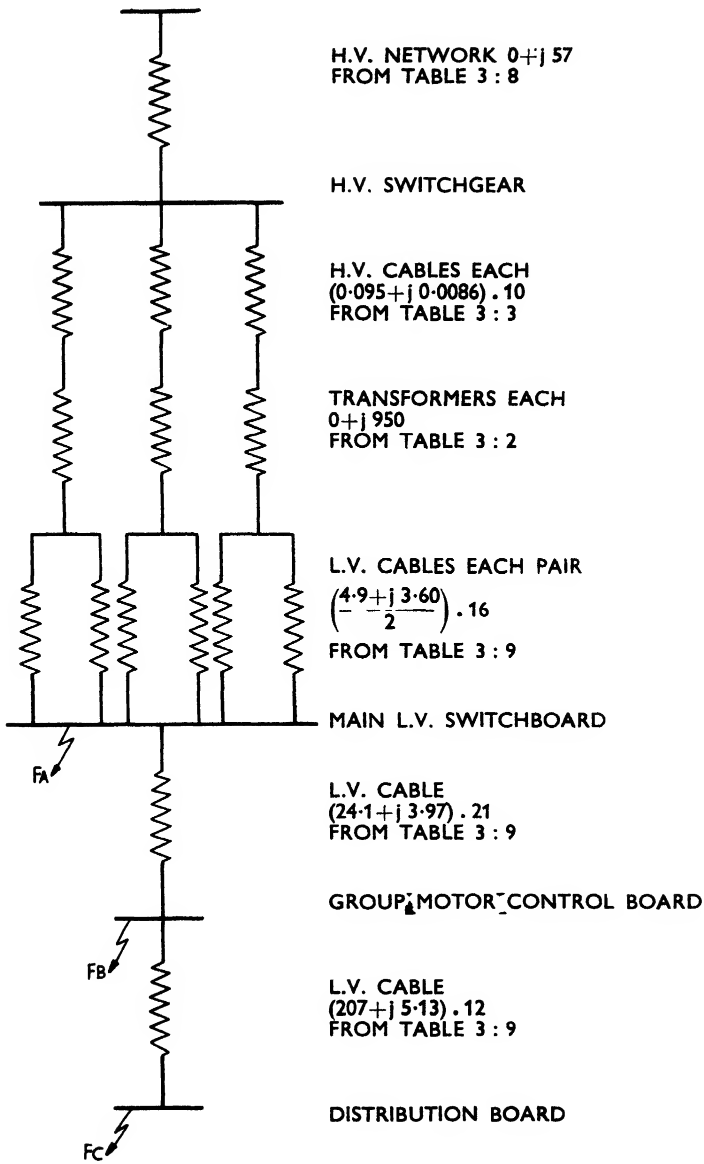

H.V. NETWORK 0+j 57
FROM TABLE 3 : 8
H.V. SWITCHGEAR
H.V. CABLES EACH
(0·095+j 0·0086) . 10
FROM TABLE 3 : 3
TRANSFORMERS EACH
0+j 950
FROM TABLE 3 : 2
L.V. CABLES EACH PAIR
$\left(\frac{4{\cdot}9+j\,3{\cdot}60}{2}\right) . 16$
FROM TABLE 3 : 9
MAIN L.V. SWITCHBOARD
FA
L.V. CABLE
(24·1+j 3·97) . 21
FROM TABLE 3 : 9
GROUP MOTOR CONTROL BOARD
FB
L.V. CABLE
(207+j 5·13) . 12
FROM TABLE 3 : 9
DISTRIBUTION BOARD
FC

FIG. 3-46.

the fault value from 25 to 14·33 MVA and also to note that resistance now exceeds reactance, so that the power factor at the fault is high with every casement that brings:—

$$\text{P.F.}=\frac{R}{Z}=\frac{519{\cdot}766}{698}=0{\cdot}745$$

To continue, for a fault at the sub-distribution board (F_C) the impedance diagram is redrawn as in Fig. 3-50 and again adding for a series circuit we get:—

Impedance to group motor control board	=	$519{\cdot}766+j\,465{\cdot}998$
Cable	=	$2\,484{\cdot}0 \quad +j\ 61{\cdot}56$
Z (Total)	=	$3\,003{\cdot}766\ +j\,527{\cdot}558$
	=	$\sqrt{3\,003{\cdot}766^2+527{\cdot}558^2}$
	=	3 046%

and the short-circuit value will be:—

$$\text{S.C. MVA}=\frac{10\,000}{3\,046}=3{\cdot}28\text{ MVA}$$

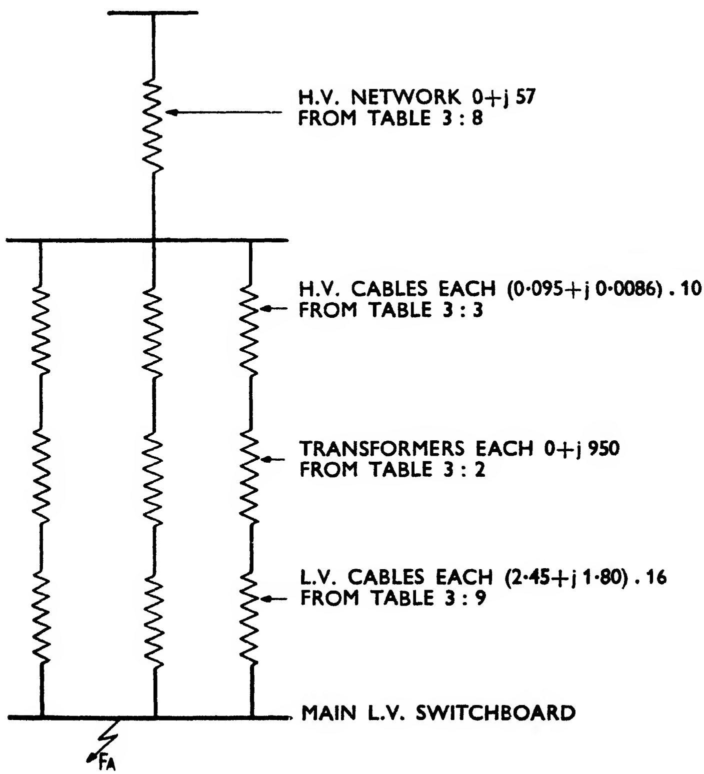


FIG. 3-47.

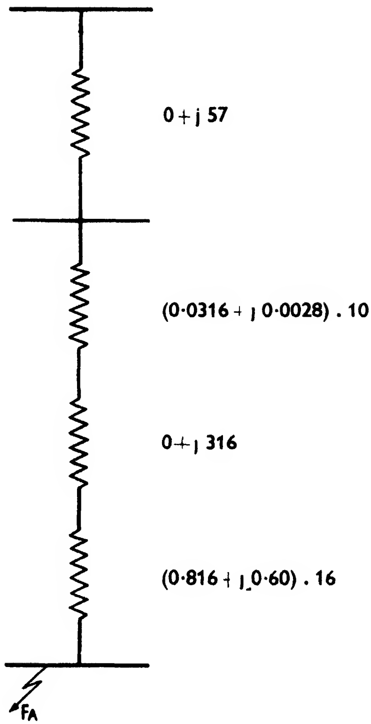


FIG. 3-48

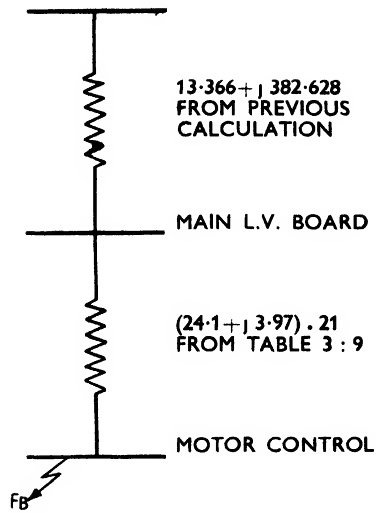


FIG 3-49

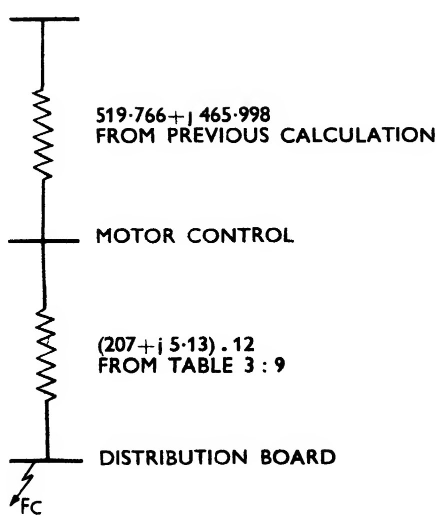


FIG. 3-50.

The examples so far considered have been simplified by reason of the fact that parallel circuits have each been of equal rating and impedance resulting in simple reduction to a single equivalent. When parallel circuits differ in the above respects the calculations to achieve the resultant imped-

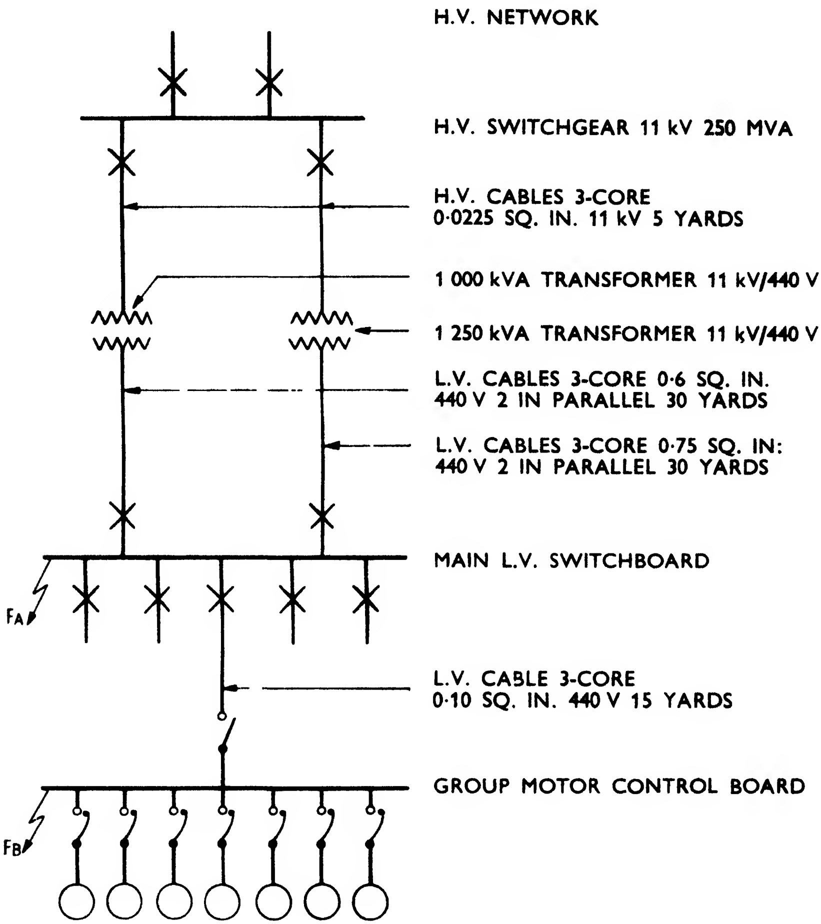


FIG. 3-51.

ances are slightly more complicated, as the example shown in Fig. 3-51 will indicate, where calculations will be made to ascertain the fault values at F_A and F_B.

Dealing with a fault at F_A first, it will be of interest initially to see what the value would be if the calculation is based on the transformer reactances

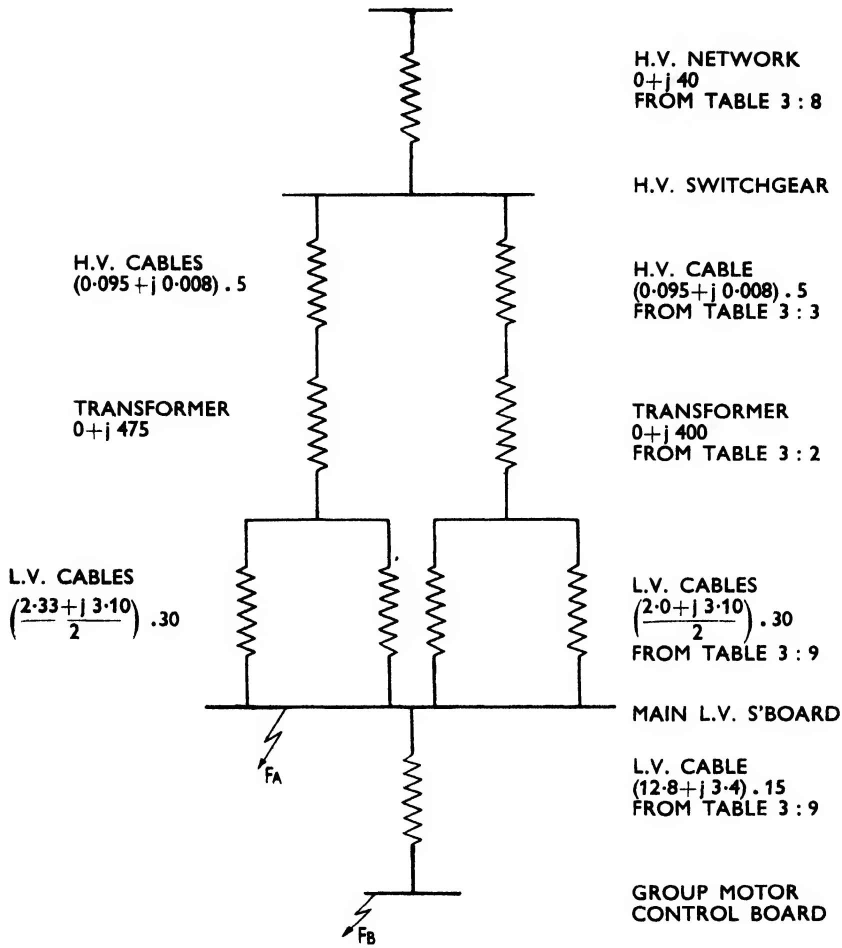


FIG. 3-52.

alone, the values (from Table 3 : 2) being 475 per cent for the 1 000 kVA unit and 400 per cent for the 1 250 kVA unit. Applying the formula for parallel circuits previously noted, the resultant impedance will be:—

$$\frac{1}{\frac{1}{475}+\frac{1}{400}}=\frac{1}{0{\cdot}0021+0{\cdot}0025}$$

$$=\frac{1}{0{\cdot}0046}=217\%$$

and the short-circuit value at the main l.v. switchboard would be:—

$$\text{S.C. MVA} = \frac{10\,000}{217} = 46 \text{ MVA}$$

This very high value is beyond the rating of standard switchgear at 440 volts so that as a next step it is of interest to include the impedance of the h.v. network which, from Table 3 : 8 for 250 MVA is 40 per cent. This value, added to that of the transformers, gives a total of 257 per cent and a new short-circuit value of

$$\text{S.C. MVA} = \frac{10\,000}{257} = 38 \cdot 9 \text{ MVA}$$

This is still high and therefore it is essential to consider the effect of the cables. The impedance diagram for the system is shown in Fig. 3-52 and it is at once clear that the small values of impedance attributable to the h.v. cables will have little effect and may be ignored. On the other hand the l.v. cables have higher values and the lengths are greater so that these may be sufficient to bring the short-circuit value down to a figure within the range of standard switchgear.

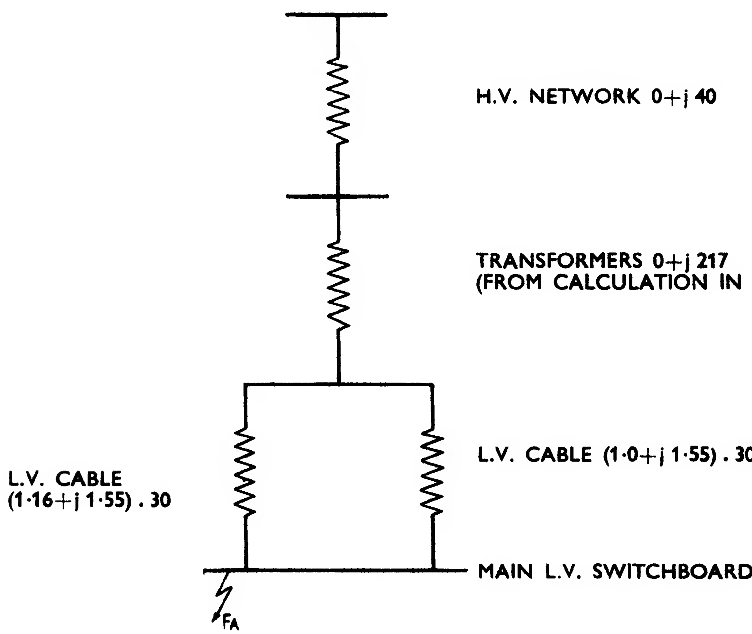


FIG. 3-53.

The first step is to reduce the parallel values of these cables and as *each* transformer has two parallel cables of equal value the impedance diagram can be reduced at once to Fig. 3-53 by dividing by 2. This leaves a parallel

circuit now of two *unequal* values and the resistance and reactance elements must be resolved separately, thus:—

$$\text{Resistance} = \frac{1}{\frac{1}{1{\cdot}16}+\frac{1}{1{\cdot}0}} = \frac{1}{1{\cdot}862} = 0{\cdot}537$$

$$\text{Reactance} = \frac{1}{\frac{1}{1{\cdot}55}+\frac{1}{1{\cdot}55}} = \frac{1}{1{\cdot}29} = 0{\cdot}77$$

so that the resultant impedance is:—

$$Z = 0{\cdot}537 + j\,0{\cdot}77$$

which has to be multiplied by 30, the length in yards, to give:—

$$Z = 16{\cdot}11 + j\,23{\cdot}1$$

and the diagram now appears as in Fig. 3-54 from which we deduce:—

$$Z = \sqrt{16{\cdot}11^2 + 280^2}$$

$$= 280\% \text{ (for all practical purposes)}$$

and the short-circuit value at F_A is now:—

$$\text{S.C. MVA} = \frac{10\,000}{280} = 35{\cdot}6 \text{ MVA}$$

This value is sufficiently near to warrant the use of standard switchgear rated at 35 MVA bearing in mind that some very slight reduction will arise due to the h.v. cables not included in the calculation.

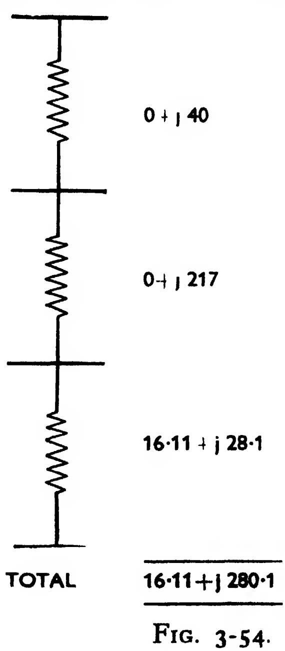


FIG. 3-54.

To ascertain the fault value at F_B on the group motor control board requires only the addition of the impedance value of the extra cable to the figures calculated so far and given in Fig. 3-54, thus:—

$$
\begin{aligned}
\text{Impedance to fault } F_B &= 16{\cdot}11 + j\,280 \\
\text{Cable to motor control board} &= 192 \quad + j\;\;51 \\
\hline
Z\ (\text{Total}) &= 208{\cdot}11 + j\,331 \\
&= \sqrt{208^2 + 331^2} \\
&= 390\%
\end{aligned}
$$

and the short-circuit value will be:—

$$\text{S.C. MVA} = \frac{10\,000}{390} = 25{\cdot}64 \text{ MVA}$$

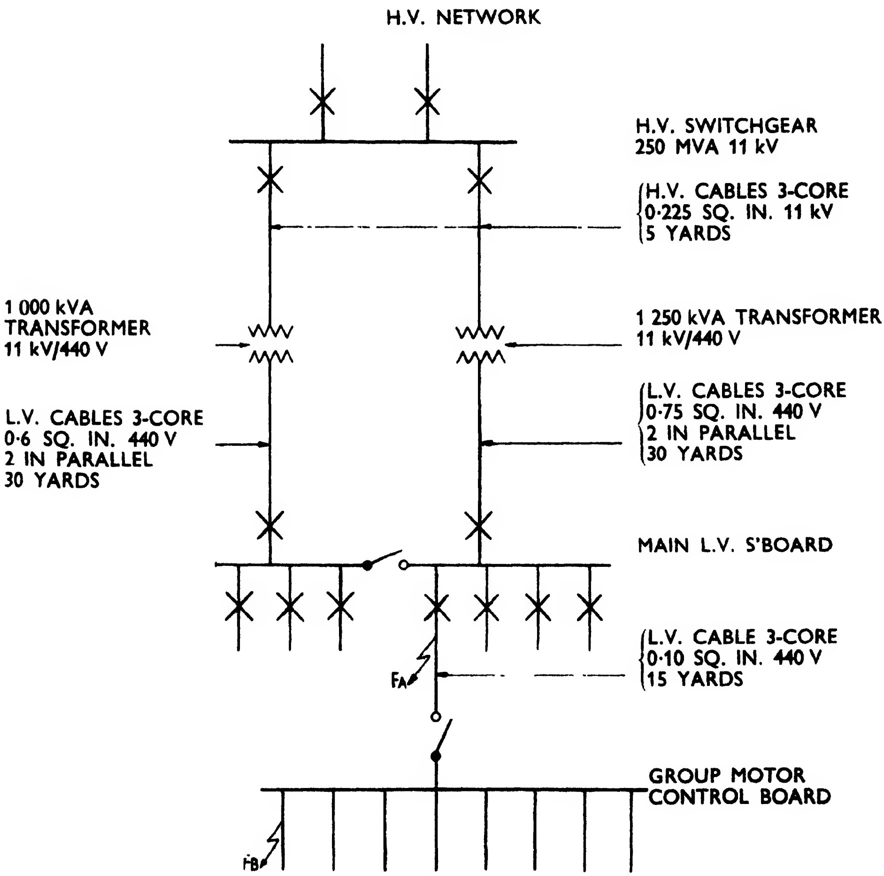


Fig. 3-55.

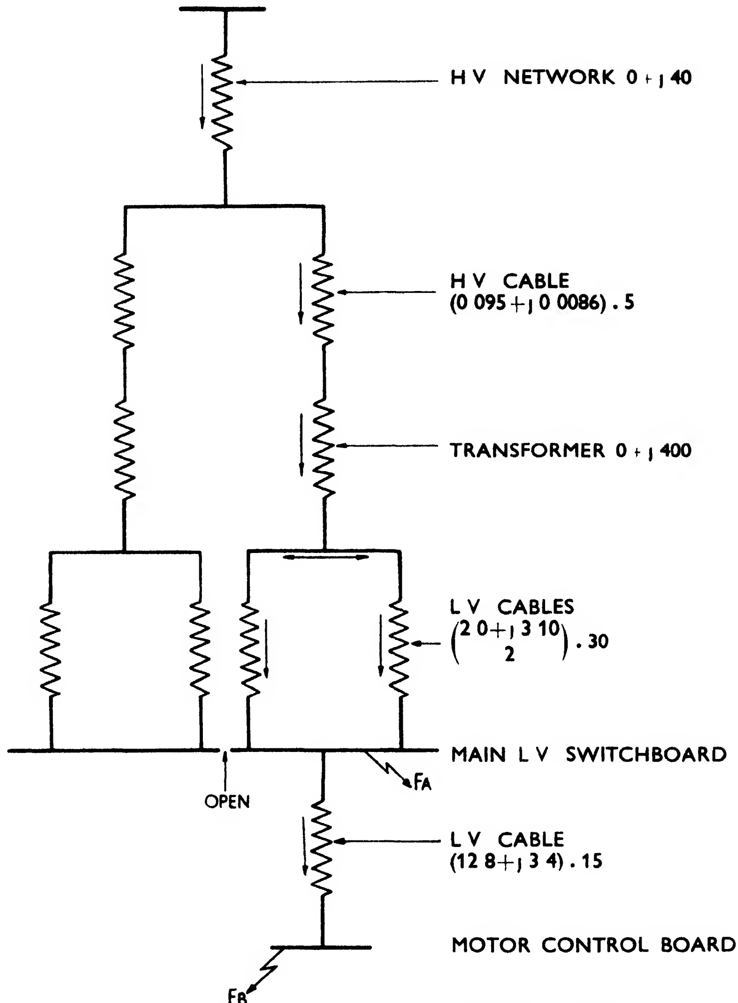


FIG 3-56

It has been noted earlier that where high fault values arise, very significant reductions can be achieved by suitably sectionalising the busbars and by way of example it is convenient to take the system shown in Fig 3-51 and arrange it in the manner shown in Fig 3-55, with suitable interlocks between the section switch (or circuit-breaker) and the two transformer circuit-breakers so that at any one time only two of these three can be closed One disadvantage of this scheme, of course, is that should the 1 250 kVA transformer be lost for any reason, there will be a complete shut-down at the motor control board until such time as the section switch can be closed This

situation could be mitigated by using, say, two 600 kVA transformers instead of one 1 250 kVA and then the loss of one unit would leave the other to maintain some supplies although load shedding might be necessary.

To investigate the possible reduction in short-circuit values the impedance diagram can be drawn as in Fig. 3-56 and, again ignoring the impedance of the h.v. cables, the impedances to a fault at F_A on the main l.v. switchboard are summed up as follows:—

H.V. network	=	0	+	j 40
Transformers	=	0	+	j 400
L.V. cables	=	30	+	j 46·5
		30	+	j 486·5

$$Z \text{ Total} = \sqrt{30^2 + 486{\cdot}5^2} = 487\%$$

and the short-circuit value will be:—

$$\text{S.C. MVA} = \frac{10\,000}{487} = 20{\cdot}5 \text{ MVA}$$

This has shown that the fault value of the main l.v. switchboard is reduced from 35·5 MVA to the much lower value of 20·5 MVA, permitting the use of switchgear with a fault rating of 25 MVA.

For a fault at F_B, we sum up as follows:—

Impedance to fault F_A	=	30	+	j 486·5
L.V. cable to control board	=	192	+	j 51·0
Z Total		222	+	j 537·5
	=	581%		

and the short-circuit value will be:—

$$\text{S.C. MVA} = \frac{10\,000}{581} = 17{\cdot}2 \text{ MVA}$$

One part of this exercise in short-circuit calculations has been to see how to arrive at true values and that this is important can be judged by a study of the electromagnetic forces which arise on busbar and connection structures, a problem which will be noted in some detail in Chapter XIV.

SHORT-TIME RATING OF CABLES

Although this book is primarily concerned with switchgear, a chapter on short-circuit calculations would not be complete without a brief reference to cables because, firstly, as the diagrams show, these have to carry the fault current for a time corresponding to the clearance time of the appropriate circuit interrupting device (circuit-breaker or fuse) and secondly, because we are depending in some instances on the impedance of the cables to assist in the reduction of short-circuit MVA. If, therefore, because of high short-circuit current values it becomes necessary to use a larger cable than normal load conditions dictate, we are reducing the amount of impedance contributed by the cable and in turn this puts up the short-circuit current so that we have all the elements of a vicious circle.

Until recently the principal limitation placed on the magnitude of the current which can be carried by a paper-insulated cable for a short time (say up to 3 seconds) has been that of the final temperature to which the conductor could be raised. From 1932 this has been generally accepted as being 120°C and on the assumption that all heat dissipated in the conductor is used in raising the conductor temperature, the short-circuit rating could be defined by a formula.

$$I \text{ r.m.s.} = k \cdot A/\sqrt{t}$$

where I r.m.s. = symmetrical value of current in kilo-amperes.

A = cross-sectional area of conductor in sq. in.

t = time in seconds (fault duration).

k = constant dependent on conductor material and its temperature at the start of the fault.

Gosland and Parr* have indicated that for copper conductors limited to a final temperature of 120°C, values of k are 86, 63, 47·5 for temperatures at the start of the fault of 15°C, 60°C and 85°C respectively. In other published data relating to paper-insulated cables, it has been given as 57 where the initial temperature of the conductor is assumed to be 70°C.

The limitation of 120°C however has been thought to be too onerous and is low by comparison with the limits accepted on the Continent and in the U.S.A. Further research has therefore recently suggested that for cables of the type concerned the safe final temperature of the conductor (copper) can be raised to 160°C resulting in new formulae in which the constant k is recommended to be 76·5 for 11 kV cables and 70 for 1 100 volt cables, thus:

$$I \text{ r.m.s.} = 76{\cdot}5 \cdot A/\sqrt{t} \text{ for 11 kV cables.}$$

$$I \text{ r.m.s.} = 70{\cdot}0 \cdot A/\sqrt{t} \text{ for 1 100 volt cables.}$$

The different constant for 11 kV and 1 100 volt cables is suggested because the normal maximum operating temperatures of 11 kV cables are usually lower than those of 1 100 volt cables.

In the past, it has been assumed that formula such as the foregoing could be used in all circumstances but it has now been shown that other factors enter into the problem, namely (a) that above certain currents, the belt insulation may burst or (b) the sheath temperature may rise above a safe value, i.e., 250°C. These investigations are reported in detail in recent papers by Gosland and Parr* and Buckingham* and these can profitably be studied by all who are concerned with cables in relation to short-circuit problems. It must be noted, however, that the papers are limited to certain types of cable, i.e. normal belted types, paper or cambric insulated up to and including 11 kV working voltage. The data given cannot be assumed to apply to other types of cable such as those using aluminium conductors, mineral insulated cables or those with p.v.c. or other insulation. Work on these is proceeding to establish a basis of short-time ratings and pending publication of data, a user should consult the cable manufacturer for guidance.

**See bibliography.*

In the paper by Buckingham, a series of curves have been produced covering various forms of cable, e.g. single-wire armoured, steel tape armoured and unarmoured. It is outside the scope of a book on switchgear to deal with each of these or the many other details which ultimately determine the short-time rating of a particular cable. Our purpose here will be achieved if the existence of the problem has been established. To emphasize the point, Tables 3 : 13, 3 : 14 and 3 : 15 are given, these relating only to single-wire armoured types and based on a maximum conductor temperature of 160°C or the current which will be safe against the possibility of bursting the belt insulation

A study of the figures will show that in many cases it may be necessary to run two or more cables in parallel to obtain a requisite short-time rating,

TABLE 3 : 13

SHORT-TIME RATINGS FOR PAPER-INSULATED CABLES 11 KV 3-CORE (BELTED) SINGLE WIRE ARMOURED TO B.S.480 : 1954

Conductor area sq in	Short-time current r m s symmetrical (kilo-amps)				
	0 2 sec	0·5 sec	1·0 sec	2·0 sec	3 0 sec
0·022 5	3·9	2 4	1·7	1·2	0·99
0·04	6·9	4 4	3 1	2·2	1·8
0·06	10	6 6	4·7	3·3	2 7
0·10	18	11	7·9	5·6	4 5
0·15	26	16	11	8 2	6·7
0·20	34	22	15	11	8·8
0·25	43*	27	19	13	11
0·30	45*	33	24	17	14
0·40	47*	45	32	22	18
0·50	50*	50*	39	27	22

NOTE *Figures marked with an asterisk are less than those given by the formula on page 68 and are the current values which are safe against the possibility of bursting the belt insulation*

R M S SYMMETRICAL VALUES OF CURRENT AGAINST MVA AND VOLTAGE

MVA	Kilo-amperes at		
	3·3 kV	6·6 kV	11·0 kV
15	2·63		
25	4·38		
50	8·16		
75	13·1	6·57	3·94
100	17·5	8·76	5·25
150	26·3	13·1	7·88
250	43·8	21·9	13·1
350		30·6	18·4
500		43·8	26·3
750			39·4

even though the normal load condition can be satisfied by one cable. This is particularly so in the 1 100 volt class, a point clearly demonstrated in Table 3 : 15 where the bursting current is related to time. Thus, on a system with a fault rating of 25 MVA at 415 volts, the smallest single cable would be 0·4 sq in. and even so, it could only withstand the short-circuit for 0·68 second. If, as is sometimes specified, the time period must be 3 seconds, then it becomes necessary to consider cables in parallel and probably of larger section If, as is indicated in the papers referred to earlier and in one by the present author,* low-voltage cables can be protected by h.r.c fuses having the advantage of "cut-off" (see Chapter XII), most problems are automatically solved, as the interrupting times are then, under maximum fault conditions, less than one half-cycle i e. 0·01 second

TABLE 3 : 14

SHORT-TIME RATINGS FOR PAPER-INSULATED CABLES 1·1 KV 4-CORE (BELTED) SINGLE WIRE ARMOURED TO B.S 480 : 1954

Conductor area sq. in	Short-time current r m s. symmetrical (kilo-amps)				
	0·2 sec	0·5 sec	1·0 sec	2·0 sec	3·0 sec
0·007	1·1	0·69	0·5	0·35	0·29
0·0145	2·3	1·5	1·0	0·74	0·6
0·0225	3·5	2·2	1·6	1·1	0·91
0·04	6·3	4·0	2·8	2·0	1·6
0·06	9·5	6·0	4·3	3·0	2·5
0·10	16	10	7·2	5·1	4·1
0·15	24	15	10	7·4	6·1
0·20	27*	20	14	9·9	8·1
0·25	29*	25	18	12	10
0·30	30*	30	22	15	12
0·40	35*	35*	29	20	17
0·50	38*	38*	36	25	20
0·60	45*	45*	43	31	25
0·75	48*	48*	48*	38	30
1·0	54*	54*	54*	51	42

NOTE—Figures marked with an asterisk are less than those given by the formula on page 68 and are current values which are safe against the possibility of bursting the belt insulation

R.M.S. SYMMETRICAL VALUES OF CURRENT AGAINST MVA AND VOLTAGE

MVA	Kilo-amperes at		
	400 V	415 V	440 V
10	14·4	13·86	13·14
15	21·6	20·8	19·60
25	36·4	35·0	33·0
35	50·7	47·8	46·0

**See bibliography*

TABLE 3 : 15

PAPER-INSULATED CABLES 1·1 KV 4-CORE (BELTED) SINGLE WIRE ARMOURED TO B.S.480 : 1954.

Conductor area sq. in	Approx. max. safe current for belt insulation kA	Approx. max time current can be carried sec	Equivalent MVA at volts		
			400 V	415 V	440 V
0·007	14	0·002	9·7	10·1	10·7
0·014 5	16	0·004	11·1	11·5	12·2
0·022 5	15	0·01	10·4	10·8	11·4
0·04	18	0·02	12·5	13·0	13·7
0·06	19	0·05	13·2	13·7	14·5
0·10	22	0·10	15·2	15·8	16·8
0·15	25	0·18	17·3	18·0	19·1
0·20	27	0·27	18·7	19·4	20·6
0·25	29	0·36	20·1	20·9	22·1
0·30	30	0·52	20·8	21·6	22·9
0·40	35	0·68	24·3	25·2	26·7
0·50	38	0·87	26·3	27·4	29·0
0·60	45	0·92	31·2	32·4	34·3
0·75	48	1·2	33·3	34·5	36·6
1·00	54	1·9	37·4	38·8	41·2

BIBLIOGRAPHY

Bulletin 169, American Bureau of Standards.

Calculation and Design of Electrical Apparatus, W. Wilson (Chapman and Hall).

Calculation and Measurement of Inductance and Capacitance, W. H. Nottage (Wireless Press, Ltd.).

Calculation of Fault Currents in Electrical Networks, R. T. Lythall (Pitman and Sons).

Calculation of Network Short-Circuits, A. Garnett (The Draughtsman Publishing Co., Ltd.).

Copper for Busbars, The Copper Development Association, Publication No. 22.

The Switchgear Handbook, Vol. II, W. A. Coates and H. Pearce (Pitman and Sons).

Simplified Short-Circuit Calculations, R. T. Lythall (The Belmos Co. Ltd.).

"ALTERNATOR REACTANCES", G. J. O. Garrard, "Electrician", August 5, 1939.

"CALCULATING FAULT CURRENTS", G. J. O. Garrard, "The Electrical Review", September 12, 1937.

"A BASIS FOR SHORT-CIRCUIT RATINGS FOR PAPER-INSULATED CABLES UP TO 11 kV". L. Gosland and R. G. Parr. Proceedings I.E.E. Paper No. 3314.S., August, 1960 (108 A, p.183).

"A Basis for Short-Circuit Ratings for Paper-Insulated Cables up to 11 kV". L. Gosland and R. G. Parr. E.R.A. Report, Ref. F/T.195, 1960.

"Calculation of Initial Symmetrical Short-Circuit Currents for the Selection of Circuit-Breakers", G. Cluley, "Metropolitan-Vickers Gazette", January, 1938.

"Calculation of Inductance and Current Distribution in L.V. Connections to Electric Furnaces", C. C. Levy, Paper presented to Summer Convention, A.I.E.E. June, 1932.

"Calculation of Short-Circuit Currents at Electrically Remote Locations", R. T. Lythall, "Iron & Coal Trades Review", Dec. 2nd, 1949.

"Engineering Calculation of Inductance and Reactance for Rectangular Bar Conductors", O. R. Schurig, "G.E. Review", May, 1933.

"Group Motor Control Boards", R. T. Lythall. "Electrical Review", 30th June, 1961.

"Low Voltage Short-Circuits", "The Electrical Times", 2nd March, 1950, p.327.

"Notes on the Calculation of Network Short-Circuits", G. J. O. Garrard, "G.E.C. Journal", February, 1937.

"Rupturing Capacity and Plant Impedance", E. A. Beavis, "The Electrician", 12th August, 1949, p.495

"Reactance Drop over Strap Conductors", G. E. Gittins, "The Metropolitan-Vickers Gazette", January, 1922.

"Short-Circuit Calculations", M. G. Say, "Electrical Engineer", August 12, 1938.

"Short-Circuit Conditions on Large Industrial L.V. Distribution Networks", T. S. G. Seaward, "Journal I.E.E.", Part I, Vol. 88, No. 3, March, 1941.

"Short-Circuit Ratings for Mains Cables". G. S. Buckingham. Proceedings I.E.E. Paper No. 3284.S. July, 1960 (108 A p.197).

"Short-Circuit Calculating Procedure for Low-Voltage A.C. Systems", A. G. Darling, American I.E.E. Technical Paper 41-67, 1940.

"Short-Circuit Currents in Low Voltage Systems", Committee Report American I.E.E. Technical Paper 55-442, 1955.

"Short-Circuit Ratings of Paper-Insulated Lead-Sheathed Cables". "Electrical Times" 16th March, 1961.

CHAPTER IV

SHORT-CIRCUIT CALCULATIONS FOR UNSYMMETRICAL FAULTS

CHAPTER IV

SHORT-CIRCUIT CALCULATIONS FOR UNSYMMETRICAL FAULTS

It has been shown in Chapter III how calculations are made for the condition of a symmetrical fault, this being the accepted method for the selection of suitably rated circuit-breakers or fuses and for the stresses set up in busbar and connection structures under short-circuit conditions. Such calculations are also adequate for determining the overcurrent factors for current transformers and protective gear stability on through faults.

Fault conditions however, are not confined to the threephase condition and indeed the majority of faults are those which involve only one line and in some cases two. Such faults are thus unsymmetrical in nature and it becomes necessary for engineers to calculate the fault currents which can occur under each of the three conditions shown in Fig. 4-1. The information obtained is necessary for the determination of protective gear relay settings and in studies of transient stability in an interconnected power system. Not only is it essential to know the current at the point of fault but also how it is distributed (and in what magnitude) throughout the network behind the fault. A full study of this subject also involves the unsymmetrical voltages which arise, a knowledge of which is essential particularly in protective systems of the directional type where the voltage element is important Here we shall concern ourselves only with the current aspect but a number of books and papers noted in the bibliography include a full study of the voltage condition

In order to calculate the values of current for unsymmetrical faults use has to be made of the theory of symmetrical components, the principles

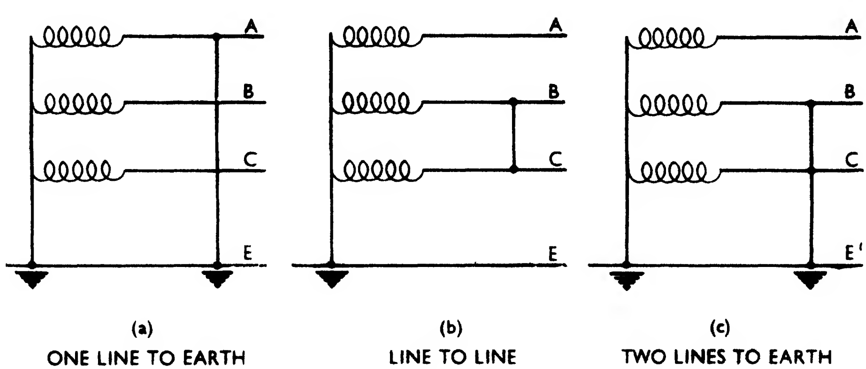


FIG. 4-1. *Types of unsymmetrical fault.*

of which were originally stated by Stovkis and were enunciated in practical form later (1918) by Fortescue. It is beyond the scope of this book to study the theoretical basis of symmetrical components but instead to accept the theory and demonstrate its practical use.

This then is the purpose of this chapter, but firstly it is necessary to state the facts established by the theory. They are:—

1. In any three phase system the occurrence of faults of the type shown in Fig. 4-1 causes unbalance, the currents and voltages becoming unequal in magnitude, while the vectors representing them are no longer spaced 120° or equal.
2. In any unbalanced system, it is possible to analyse that system into two or three balanced systems known as positive, negative, and zero phase sequences.
3. The positive phase sequence system is that system in which the phase or line currents or voltages reach a maximum in the same cyclic order as those in a normal supply, *e.g.*, assuming the conventional counter-clockwise rotation, then the positive phase sequence vectors are those shown at (*a*) in Fig. 4-2. A balanced system corresponding to normal conditions contains a positive phase sequence only. It is also the condition for a three phase fault as calculated in Chapter III.
4. The negative phase sequence system is that system in which the vectors still rotate anti-clockwise but reach a maximum in a reverse order, *i.e.*, A.C.B. as indicated at (*b*) Fig. 4-2. This sequence only arises under

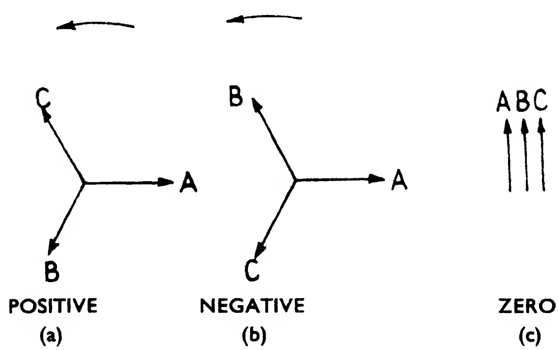


FIG. 4-2.

conditions of unbalance as when faults of the type shown in Fig. 4-1 occur, such faults contain also the positive sequence system as (3) above and, in the case of faults to earth, a zero phase sequence system as noted in (5) below.

5. The zero phase sequence system is a single phase vector system combining three equal vectors in phase, as shown at (*c*) Fig. 4-2, and represents the residual current or voltage present under fault conditions on a three phase system with a fourth wire or earth return present. Clearly the zero phase sequence embraces the ground therefore, in addition

to the three line wires and represents a fault condition to earth or to a fourth conductor if present. Its presence arises only where fault to earth currents can return to the system via the star point of that system or via an artificial neutral point provided to earth a delta system. In an earth fault, positive and negative phase sequences are also present.

This is the basis of the theory from which it is possible to calculate the fault current under any condition. As the three phase fault has been dealt with in Chapter III, our concern here will be with:—

(a) Single phase line to line faults involving the positive and negative phase sequences and

(b) Single phase line to earth faults involving the positive, negative and zero phase sequences.

The impedances to these phase sequence currents are important to the calculations and as differences arise as between types of plant, cables and transmission lines, some idea of the values must be noted before proceeding to typical calculations. For easy reference, particularly in the worked examples, the three impedances will be given the following notation:—

Z_1 = Positive phase sequence impedance

Z_2 = Negative phase sequence impedance

Z_0 = Zero phase sequence impedance

In all *static* plant (and this includes cables and overhead lines) $Z_1 = Z_2$ but may differ from Z_0. In *rotating* plant, however, all three are different.

In power transformers, Z_1 and Z_2 are equal and are the normal impedances quoted by the manufacturer but Z_0 will depend on the transformer connections. For those with delta/star (star neutral earthed) star/star (both neutrals earthed) and star or delta/interstar (interstar neutral earthed) connections, Z_0 is equal to Z_1 and Z_2. For star/star connected transformers where the primary is three-wire and providing the core is of the three-limb type, Z_0 will be approximately 0·66 times Z_1. In the case of a three phase shell type or a group of three single phase transformers, Z_0 may be as high at 4 or 5 times Z_1. For all other connections, it may be assumed that there is an open circuit to zero phase sequence currents.

In cables and overhead transmission lines, Z_1 and Z_2 are equal and are the ohmic values given in manufacturers tables. On the other hand, Z_0 is only determined by calculations of some complexity, involving in the case of cables a knowledge of sheath resistances, conductor spacing, how laid and whether earthed or not, while for overhead lines the value varies with regard to single or double circuit lines, with or without earth wires and whether the latter are magnetic or non-magnetic.

Because of these complications, Z_0 can only be accurately determined for a specific case but a number of authors have given approximations which can be used for general calculations, these approximations being as follows:—

Cables

Three core	$Z_0 = 3Z_1$ to $5Z_1$
Single core	$Z_0 = 1{\cdot}25Z_1$

Overhead lines, single circuit	
No ground wire	$Z_0=3{\cdot}5Z_1$
Steel ground wire	$Z_0=3{\cdot}5Z_1$
Non-magnetic ground wire	$Z_0=2Z_1$
Overhead lines, double circuit	
No ground wire	$Z_0=5{\cdot}5Z_1$
Steel ground wire	$Z_0=5Z_1$
Non-magnetic ground wire	$Z_0=3Z_1$

A large part of the zero sequence impedance for cables is resistive and it is here that many variations occur, dependent on the earthing conditions. In a paper by Wagner and Evans, for example, the detailed calculations are given for a three core cable 450 000 c.m. 13·2 kV, the cable being buried in damp earth. These authors show that for this case:—

$$Z_1=0{\cdot}146+j\,0{\cdot}169 \text{ ohms per phase}$$
$$Z_0=1{\cdot}42\ +j\,0{\cdot}78 \text{ ohms per phase}$$

so that zero sequence resistance is nearly ten times the positive sequence resistance, while the zero sequence reactance is only 4·6 times the positive sequence reactance, and it is stated that these multiples may be used for approximations.

In the case of rotating plant where all three values differ, Z_1 is the normal value quoted by the manufacturer, *i.e.* the values used in three phase short-circuit calculations as in Chapter III. In certain circumstances, as for example where a long time delay may be applied to a protective system, it will be necessary to use the synchronous or steady state impedance, as, after several seconds, the initial short-circuit current will have fallen to the much lower steady state value. Alternatively, standard decrement curves can be applied to the calculated initial values.

Z_2 for rotating machines is generally somewhat less than Z_1 and varies with the type of winding, type of machine, number of poles, etc. and it is important in any particular calculation to ascertain the value from the machine designer. As we are only concerned here with demonstrating the use of symmetrical components it will suffice if we assume that $Z_2=0{\cdot}73Z_1$.

Similar factors concern the value of Z_0 for rotating machines and here again various authors give average values for use if actual figures are not available. These average values indicate that at 11 kV, Z_0 is equal to about $0{\cdot}33Z_1$, while at 22 and 33 kV it is about $0{\cdot}5Z_1$.

In calculations for line to earth faults, one further impedance may be present and considered, namely that which may be purposely introduced in the neutral connection to earth (see Chapter XX) and which may be either a resistance or a reactor. The value of this impedance must be multiplied by three as it is in series with each line.

For the sake of simplicity, the typical calculations which follow will be on the basis that the various impedances are purely reactive, *i.e.* that Z will be R+jX where R is zero. It has, however, been shown in Chapter III that where cables or overhead lines are included in any calculation, resistance often plays a most important part in reducing the value of fault current.

It will be remembered too that all calculations in Chapter III were on a percentage impedance basis and that normal values were converted to others on a chosen kVA base.

Examples included in that chapter could with equal ease have been calculated using ohmic values and as an exercise, these will be used in the first example to be given. But here it must be noted that when working with ohmic values, it is necessary to use a base voltage instead of kVA. Where only one voltage is involved this can be used as the base but where step-up or step-down transformers are included, then all calculations must be on a chosen voltage

Using the ohmic method and a base voltage requires formula for conversion, and those essential to the calculations are:—

1 Given the percentage reactance (or impedance) of a machine or transformer of known kVA rating:—

$$\text{Ohmic value} = \frac{\%\ \text{value} \cdot 10 \cdot \text{kV}^2}{\text{kVA}}$$

where kV = kilovolts between lines.

2 Given the ohmic value of reactance (or impedance) of a cable or overhead line at working (normal) voltage:—

$$\text{Ohmic value at base voltage} = \text{Ohmic value at normal voltage} \cdot \left(\frac{V_2}{V_1}\right)^2$$

where V_1 = normal voltage in volts

and V_2 = base voltage in volts

As a first example, assume a simple network as in Fig. 4-3 where it is required to ascertain the fault currents for a fault at F under two conditions,

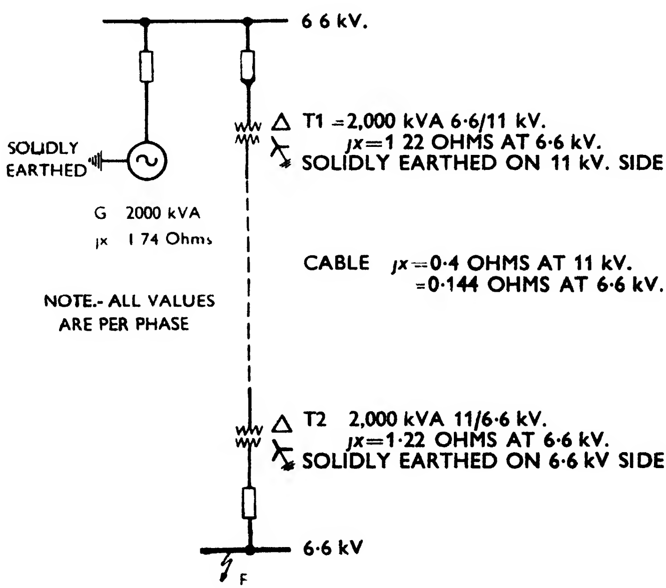


FIG. 4-3

i.e. line to line and one line to earth. Here two voltages are concerned (6·6 and 11 kV) and as the fault is assumed to be on the 6·6 kV system, it is convenient to use this voltage as a base.

The generator of 2 000 kVA has a reactance of 8 per cent and from the formula just given we find:—

$$\text{Ohmic reactance} = \frac{8 \cdot 10 \cdot 6{\cdot}6^2}{2\,000} = 1{\cdot}74 \text{ ohms}$$

The transformers each of 2 000 kVA with a reactance of 5·6 per cent are converted to:—

$$\text{Ohmic reactance of each transformer} = \frac{5{\cdot}6 \cdot 10 \cdot 6{\cdot}6^2}{2\,000} = 1{\cdot}22 \text{ ohms}$$

(Note that this value is at our chosen base of 6·6 kV.)

The cable between the two transformers has a reactance of 0·4 ohms at 11 kV and converting this to a value on a 6·6 kV base, we get

$$0{\cdot}4 \cdot \left(\frac{6\,600}{11\,000}\right)^2 = 0{\cdot}144 \text{ ohms.}$$

Bearing in mind previous notes concerning the relative values of Z_1, Z_2 and Z_0, the figures relating to Fig. 4-3 may be summarised thus: —

Z_1 Generator—Positive phase sequence impedance— $0+j1{\cdot}74$ ohms
Z_2 ,, Negative ,, ,, ,, $=(0+j1{\cdot}74) \cdot 0{\cdot}73$
$0+j1{\cdot}27$ ohms

Transformer No. 1

Z_1 ,, -Positive phase sequence impedance- $0+j1{\cdot}22$ ohms
Z_2 ,, Negative ,, ,, ,, – $0+j1{\cdot}22$ ohms

Z_1 Cable —Positive phase sequence impedance = $0+j0{\cdot}144$ ohms
Z_2 ,, -Negative ,, ,, ,, $0+j0{\cdot}144$ ohms

Transformer No. 2

Z_1 ,, —Positive phase sequence impedance - $0+j1{\cdot}22$ ohms
Z_2 ,, —Negative ,, ,, ,, - $0+j1{\cdot}22$ ohms
Z_0 ,, —Zero ,, ,, ,, – $0+j1{\cdot}22$ ohms

It will be noted that the only area where zero phase sequence current can appear is at Transformer No. 2, *i.e.*, a line fault to earth at F back to the 6·6 kV neutral of this transformer via the ground.

The three sequences can now be set down as indicated in Fig. 4-4 and adding the various impedances in series arithmetically, obtain:—

	Z_1	Z_2	Z_0
Generator	$0+j1{\cdot}74$	$0+j1{\cdot}27$	
Transformer (1)	$0+j1{\cdot}22$	$0+j1{\cdot}22$	–
Cable	$0+j0{\cdot}144$	$0+j0{\cdot}144$	
Transformer (2)	$0+j1{\cdot}22$	$0+j1{\cdot}22$	$0+j1{\cdot}22$
	$0+j4{\cdot}324$	$0+j3{\cdot}854$	$0+j1{\cdot}22$

With these values, we can proceed to calculate for the two fault conditions as follows.

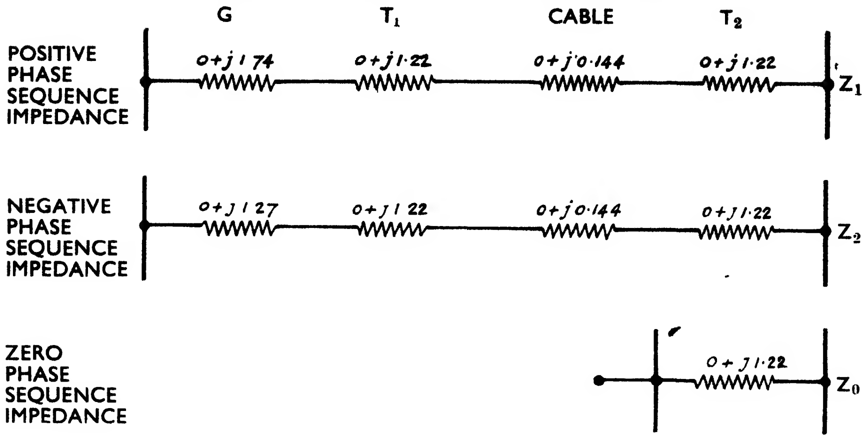


FIG. 4-4.

LINE TO EARTH FAULT

As explained earlier, faults to earth embrace the three sequence components and therefore the total impedance to the fault will be,

$$Zt \quad Z_1+Z_2+Z_0$$
$$0+j4{\cdot}324+0+j3{\cdot}854+0+j1{\cdot}22$$
$$0+j9{\cdot}398 \text{ ohms.}$$

The earth fault current will be

$$If \quad \frac{3E^*}{Zt}$$

where E Normal line to neutral voltage of the selected base voltage.

$$\therefore If = \frac{3\times 3\,810}{9{\cdot}398} \quad 1\,217 \text{ amperes.}$$

The condition at the fault can be shown as in Fig 4-5.

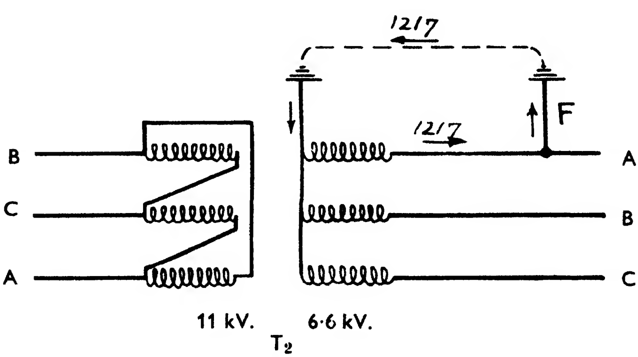


FIG. 4-5.

* *The derivation of this formula is given in detail in the article by Reeves and the book by Rissik. Both are noted in the bibliography.*

LINE TO LINE FAULT

In this case, only the positive and negative phase sequence impedances will limit the fault and

$$Zt = Z_1 + Z_2$$
$$= 0 + j4{\cdot}324 + 0 + j3{\cdot}854$$
$$= 0 + j8{\cdot}178 \text{ ohms}$$

$$\text{and } If = \frac{\sqrt{3}E^*}{Zt}$$

$$= \frac{\sqrt{3}.3\,810}{8{\cdot}178} = 806 \text{ amperes.}$$

The condition at the fault can be shown as in Fig. 4-6.

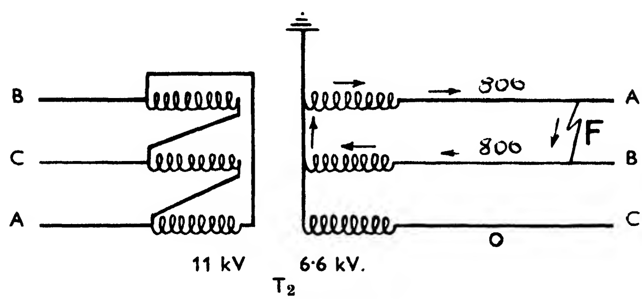


FIG. 4-6.

We have seen, therefore, that there is a considerable difference in fault current as between line to earth and line to line faults, and any protective gear installed must be sensitive to these different values. By a calculation similar to those undertaken in Chapter III it can be shown that the three phase fault current at F would be 880 amperes, so that there are three different values for different fault conditions.

Alternatively the three phase value could be determined from:—

$$If = \frac{E}{Z_1} = \frac{3\,810}{4{\cdot}324} = 880 \text{ amperes.}$$

In the calculation for a line to earth fault, the earth resistance has been assumed zero. This is a condition which is unlikely as, apart from any resistance which may be purposely installed in the neutral connection to limit the earth fault current, *e.g.*, to twice full load current with line to neutral voltage impressed, there is the resistance of the return path to the neutral. Let us assume that this is 2 ohms and this has to be multiplied by three as noted earlier.

**The derivation of this formula is given in detail in the article by Reeves and the book by Rissik Both are noted in the bibliography*

For a line to earth fault, the total impedance will now be,

$$\begin{aligned} Zt &= 0+j4{\cdot}324+0+j3{\cdot}854+6+j1{\cdot}22 \\ &= 6+j9{\cdot}398 \\ &= \sqrt{6^2+9{\cdot}398^2} = 11{\cdot}15 \text{ ohms} \end{aligned}$$

$$\text{and } If = \frac{3.3\,810}{11{\cdot}15} = 1\,025 \text{ amperes}$$

as compared with 1 217 amperes previously calculatde with zero resistance.

In addition, the cable which joins transformer T2 to its 6·6 kV switchgear will have some value of Z_1, Z_2 and Z_0 which will tend to further reduce the value of earth fault current.

We have now determined the fault currents which arise at the point of fault. It now remains to determine the distribution back to the source, proceeding as follows:—

LINE TO EARTH FAULT

The positive, negative and zero phase sequence currents in the fault are equal and each are one-third of If*, so that

$$If_1 = If_2 = If_0 = If/3,$$

where If_1 = Positive phase sequence current
If_2 = Negative phase sequence current
If_0 = Zero phase sequence current

and in the faulty phase A the total fault current If_A is the sum of the three sequence currents I_1, I_2 and I_0 and

$$If_1 + If_2 + If_0 = If = If_A.$$

The total fault current in the phases B and C is given by,

$$\begin{aligned} If_B &= I_0 + a^2 I_1 + aI_2 \\ If_C &= I_0 + aI_1 + a^2 I_2 \end{aligned}$$

where the vector operators a and a^2 are

$$a = -\tfrac{1}{2} + j\frac{\sqrt{3}}{2} = -0{\cdot}5 + j0{\cdot}866$$

$$a^2 = -\tfrac{1}{2} - j\frac{\sqrt{3}}{2} = -0{\cdot}5 - j0{\cdot}866$$

so that,

$$\begin{aligned} If_B &= I_0 + I_1(-0{\cdot}5 - j0{\cdot}866) + I_2(-0{\cdot}5 + j0{\cdot}866) \\ &= I_0 - 0{\cdot}5\,(I_1 + I_2) - j0{\cdot}866\,(I_1 - I_2) \\ If_C &= I_0 + I_1(-0{\cdot}5 + j0{\cdot}866) + I_2(-0{\cdot}5 - j0{\cdot}866) \\ &= I_0 - 0{\cdot}5\,(I_1 + I_2) + j0{\cdot}866\,(I_1 - I_2) \end{aligned}$$

In the example, a 6·6 kV star base has been used. To obtain the true currents at 11 kV, *i.e.*, in the secondary of T_1 and the primary of T_2, account must be taken of the phase displacement which occurs in respect to the

**See analytical study in "The Switchgear Handbook" (volume two) and "Elements of Symmetrical Component Theory", both noted in the bibliography.*

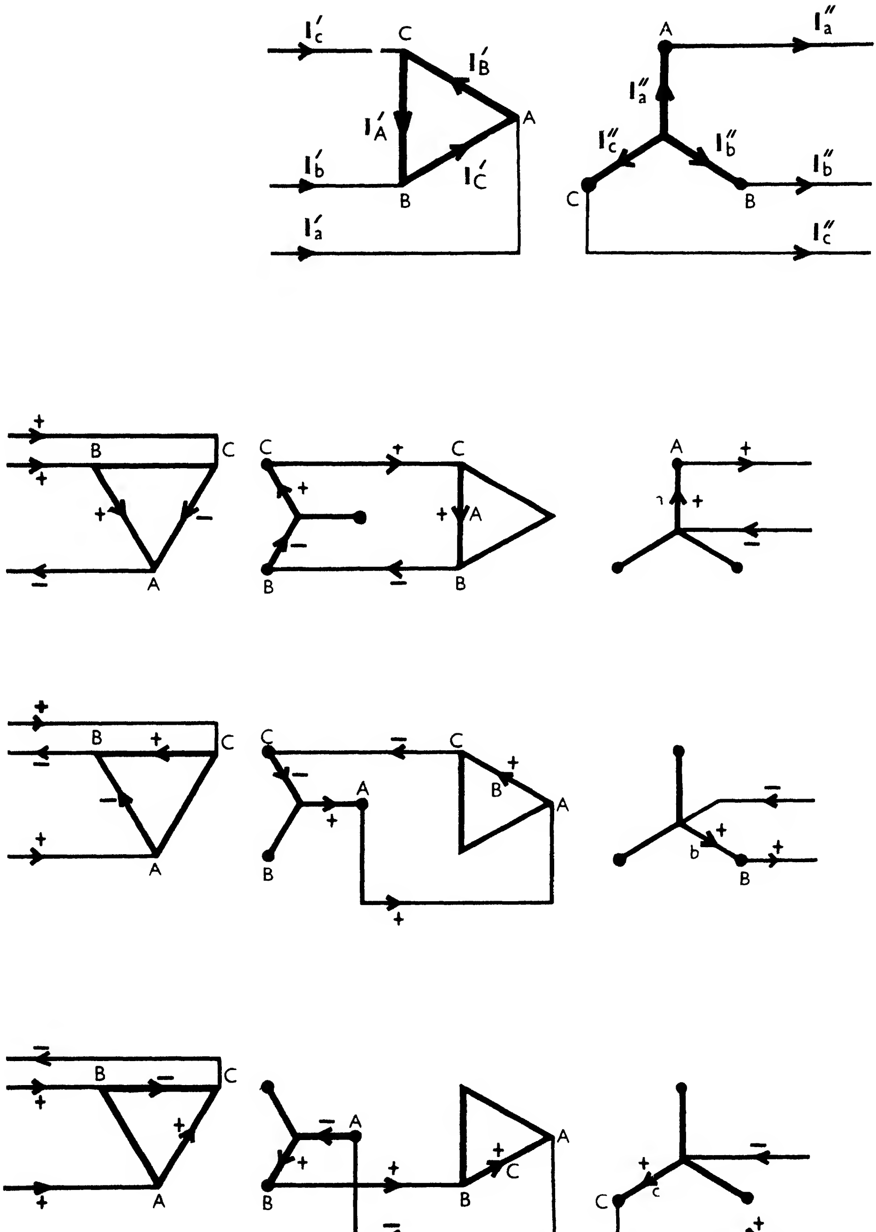


FIG 4-7

6·6 kV star base. The equations for such conversions are as follows, which should be read in conjunction with Fig. 4-7.

$$I'_a = n\,(I''_b - I''_c) = I'_B - I'_C$$
$$I'_b = n\,(I''_c - I''_a) = I'_C - I'_A$$
$$I'_c = n\,(I''_a - I''_b) = I'_A - I'_B$$

where n equals the turns per phase ratio of transformation in the direction of transformation being considered and

$I'_a\ I'_b\ I'_c$ = Converted line currents being sought,
$I''_a\ I''_b\ I''_c$ = Line currents on star base.

With this essential data, the calculations are as follows, using the total value to earth of 1 217 amperes.

If_1 = Positive sequence network current $= 1\,217/3 = 406$ amperes
If_2 = Negative sequence network current $= 1\,217/3 = 406$ amperes
If_0 = Zero sequence network current $= 1\,217/3 = 406$ amperes

If_A in Secondary Line T2 $= If_1 + If_2 + If_0 = 1\,217$ amperes
If_B in Secondary Line T2 $= I_0 + a^2I_1 + aI_2$
$= I_0 - 0{\cdot}5\,(I_1 + I_2) - j0{\cdot}866\,(I_1 - I_2)$
$= 406 - 0{\cdot}5\,(812) - j0{\cdot}866\,(0)$
$= 406 - 406 = 0$ amperes.

If_C in Secondary Line T2 $= I_0 + aI_1 + a^2I_2$
$= I_0 - 0{\cdot}5\,(I_1 + I_2) + j0{\cdot}866\,(I_1 - I_2)$
$= 406 - 0{\cdot}5\,(812) + j0{\cdot}866\,(0)$
$= 406 - 406 = 0$ amperes.

If_A in Primary Line T2 $= -0{\cdot}346\,(0 - 0) = 0$ amperes
If_B in Primary Line T2 $= -0{\cdot}346\,(0 - 1\,217) = 422$ amperes
If_C in Primary Line T2 $= -0{\cdot}346\,(1\,217 - 0) = -422$ amperes.

NOTE. $-0{\cdot}346$ is the turns per phase ratio of transformation, *i.e.*,

$$\frac{6\,600}{11\,000 \cdot 1{\cdot}73} = 0{\cdot}346$$

The minus sign before the turns ratio indicates a reversal of line currents brought about by the cascade delta/star transformations.

If_A in Primary Line T1 $= -0{\cdot}96\,(422 - (-422)) = -810$ amperes
If_B in Primary Line T1 $= -0{\cdot}96\,(-422 - 0) = 405$ amperes
If_C in Primary Line T1 $= -0{\cdot}96\,(0 - 422) = 405$ amperes.

NOTE. $-0{\cdot}96$ is the turns per phase ratio of transformation, *i.e.*,

$$\frac{11\,000}{6\,600 \cdot 1{\cdot}73} = 0{\cdot}96$$

Where positive values of current appear, this indicates flow in the direction of the fault. Negative values indicate flow in the opposite direction.

The values of current having now been calculated in each line for the complete network up to the fault, the values may be conveniently shown in a diagram as Fig. 4-8.

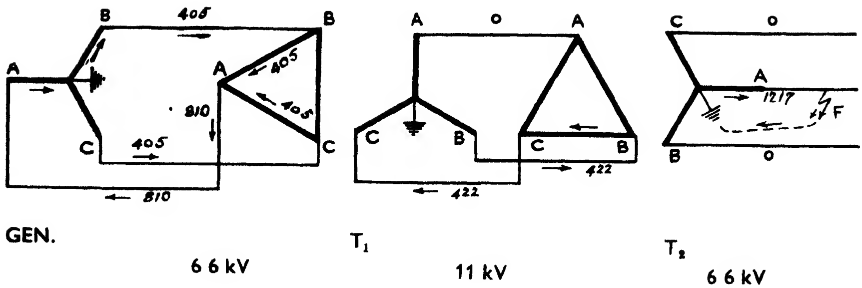


FIG 4-8

LINE TO LINE FAULT

It has been shown that a fault between lines A and B has a current value of 806 amperes. There will be no current in line C For the line to line condition, the positive and negative phase sequences only are involved and the sequence currents I_1 (positive) and I_2 (negative) are,

$$I_1=\tfrac{1}{3}\,(I_A+aI_B+a^2I_C)$$
$$=\tfrac{1}{3}\,[I_A+I_B\,(-0{\cdot}5+j0{\cdot}866)+I_C\,(\;0{\cdot}5-j0{\cdot}866)]$$
$$=\frac{806-806\,(-0{\cdot}5+j0{\cdot}866)+0}{3}$$
$$=\frac{806+403\;-j697}{3}=403-j232{\cdot}3$$
$$I_2=\tfrac{1}{3}\,(I_A+a^2I_B+aI_C)$$
$$=\tfrac{1}{3}\,[I_A+I_B\,(-0{\cdot}5-j0{\cdot}866)+I_C\,(-0{\cdot}5+j0{\cdot}866)]$$
$$\frac{806-806\,(-0{\cdot}5-j0{\cdot}866)+0}{3}$$
$$=\frac{806+403+j697}{3}\quad 403+j232{\cdot}3$$

The total fault current is the sum of the two sequence network currents thus,

$$I_1=403-j232{\cdot}3$$
$$I_2=\underline{403+j232{\cdot}3}$$
$$I_f=806 \text{ amperes}$$

The currents in the line throughout the complete circuit can be solved as follows:—

I_A in Secondary Line T2 = 806 amperes
I_B in Secondary Line T2 = −806 amperes
I_C in Secondary Line T2 = 0 amperes
I_A in Primary Line T2 = −0·346 (−806−0) = 279 amperes
I_B in Primary Line T2 = −0·346 (0−806) = 279 amperes
I_C in Primary Line T2 = 0·346 (806−(−806)) = −558 amperes
I_A in Primary Line T1 = −0·96 (279−(−558)) = − 806 amperes
I_B in Primary Line T1 = −0·96 (−558−279) = 806 amperes
I_C in Primary Line T1 = −0·96 (279−279) = 0 amperes

The values may now be included in a diagram of the network as shown in Fig. 4-9.

The purpose of calculations such as the foregoing, for line to earth and line to line faults, may be seen by an inspection of the two diagrams Figs. 4-8 and 4-9. In these we see the currents at each point in the network for faults at a remote point.

It is clear that unless some form of discriminating protection be applied, there is every indication that, for a fault at the point chosen for our example, the generator and the transformers will all be disconnected by the through fault current. For example, the normal current of the generator is 175 amperes, and for both types of fault, currents considerably in excess of normal are experienced. If simple overcurrent be fitted, high settings would be essential to avoid operation.

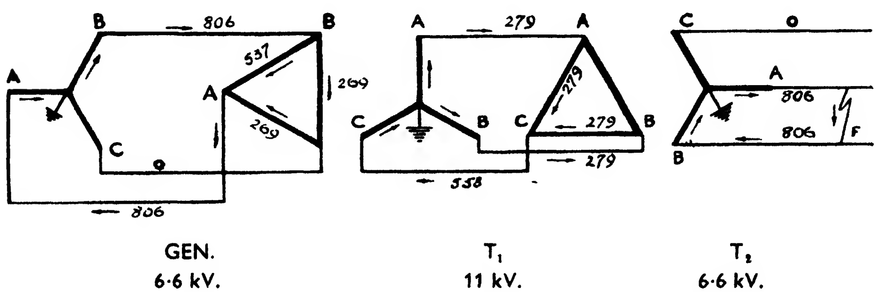


FIG. 4-9.

A second example may be worked using the percentage reactance method and a common kVA base. For this purpose, a system is shown in Fig. 4-10 and it will be our task to ascertain the fault current at a point close up to the 400 volt busbars at Substation C, on the occurrence of an earth fault between phase A and ground. The reactances indicated in the diagram are those to the positive phase sequence currents. The first task, as in three phase fault calculations, is to convert all reactances to a common base, *e.g.*, 100 000 kVA as follows using the formula noted in Chapter III:—

Generators G1 and G2 $= \dfrac{100\ 000}{10\ 000} \cdot 20 = 200\%$ each

Transformers T1 and T2 $= \dfrac{100\ 000}{5\ 000} \cdot 6{\cdot}8 = 136\%$ each

Overhead Line $= \dfrac{100\ 000 \cdot 100\ 000}{(33\ 000)^2} \cdot 3{\cdot}6 = 33\%$

Generator G3 $= \dfrac{100\ 000}{2\ 000} \cdot 12 = 600\%$

Transformer T3 $= \dfrac{100\ 000}{1\ 500} \cdot 5{\cdot}3 = 353\%$

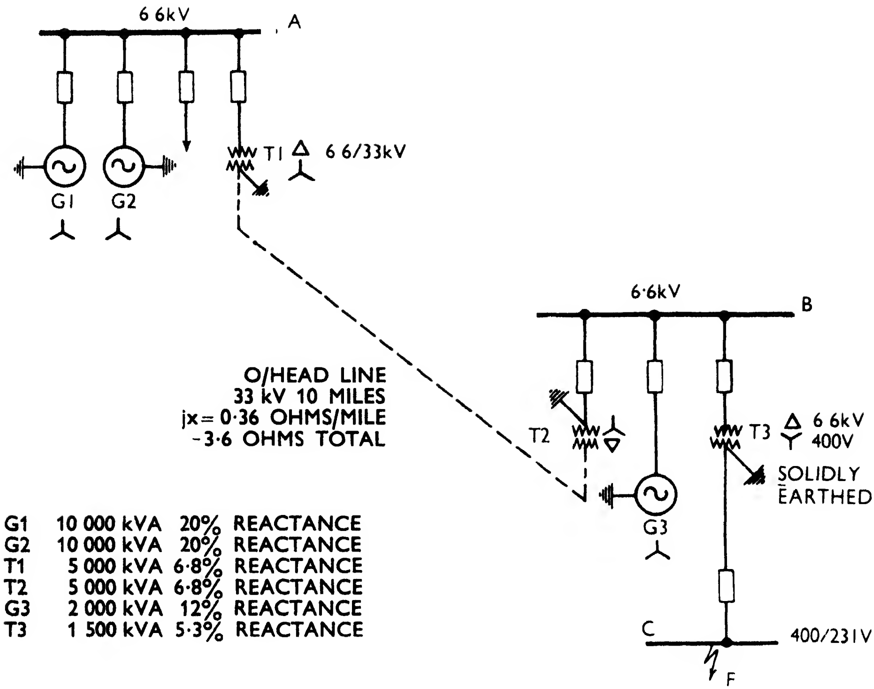


FIG. 4-10.

The positive, negative and zero phase sequence reactances are:

	Z_1		Z_0
Generators G1, G2 .		146%	
Transformers T1, T2	136%	136%	
Overhead Line .	33%	33%	
Generator G3 .	600%	438%	
Transformer T3 .	353%	353%	353%

NOTE.—In the table above the blanks under Z_0 for generators G1, G2 and G3 and transformers T1 and T2 do not imply that these have no zero phase sequence impedance but simply that no path exists at these neutrals for the return of earth fault current originating on the 400 volt system beyond T3.

Following the procedure when calculating three-phase symmetrical faults, a series of network reduction diagrams are deduced in order that a single reactance to the fault may be ascertained. In this case, however, separate diagrams are required for each of the phase sequences, and Fig. 4-11 is a set of reactance diagrams for the original network. These can be reduced at once, by combining parallel values, and adding series values, to Figs. 4-12 and 4-13.

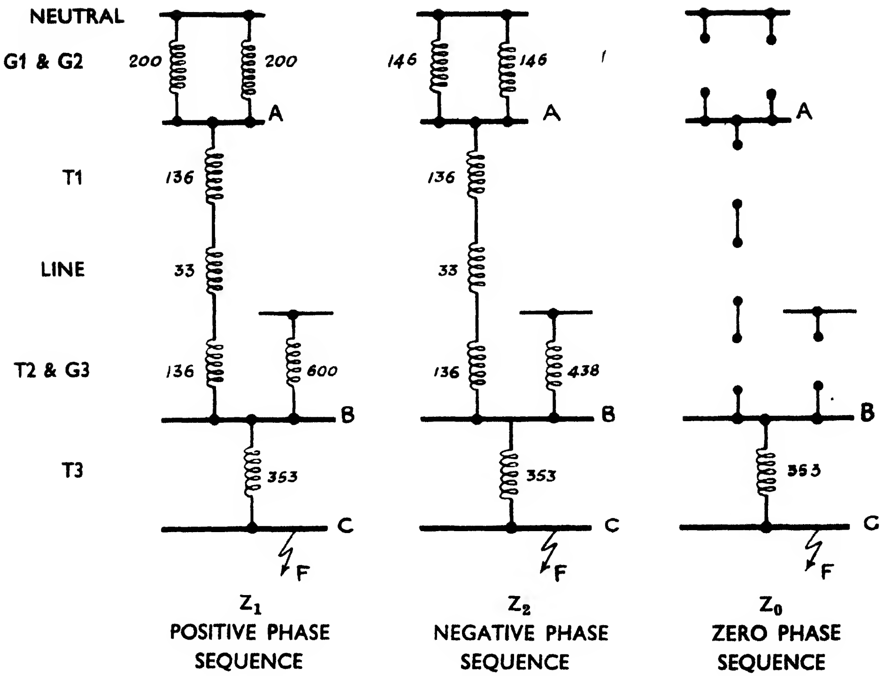


Fig. 4-11.

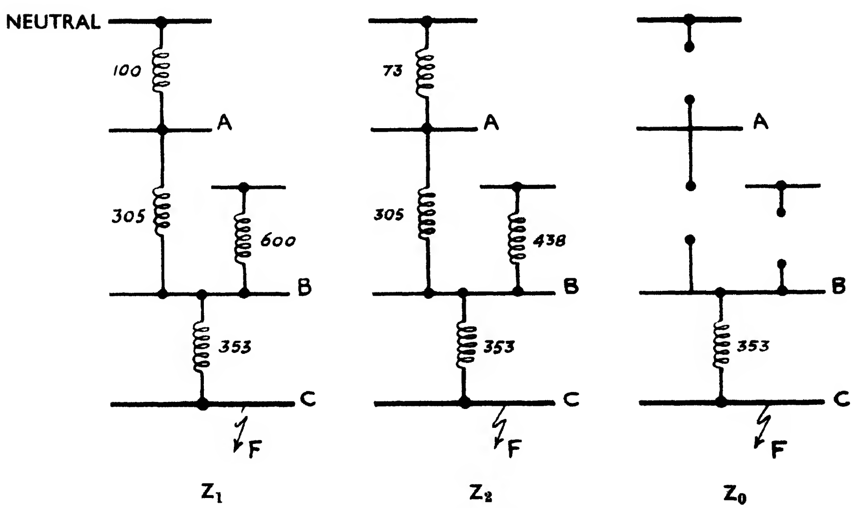


Fig. 4-12.

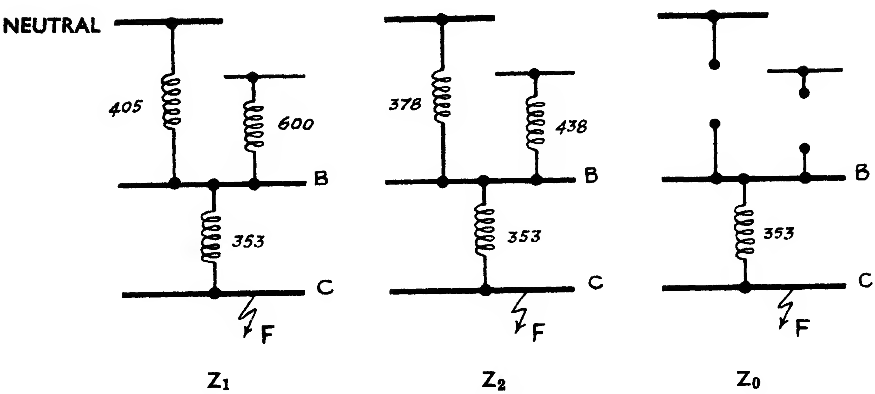


FIG. 4-13.

Values in parallel in Fig. 4-13 are evaluated as follows.

$$\text{Positive network} \quad \frac{1}{\frac{1}{405}+\frac{1}{600}} = 241\%$$

$$\text{Negative network} \quad \frac{1}{\frac{1}{378}+\frac{1}{438}} = 203\%$$

and the network diagrams now become Fig. 4-14. From this we determine that,

$$Z_1 = 594\%$$
$$Z_2 = 556\%$$
$$Z_0 = 353\%$$

and the total reactance (Zt) to the fault is

$$Zt = Z_1 + Z_2 + Z_0 = 1\,503\%$$

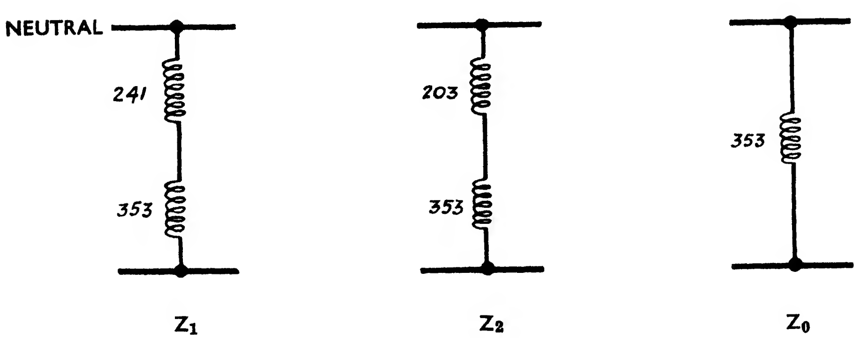


FIG. 4-14.

and the fault current to earth is

$$If = \frac{3I \cdot 100}{Zt}$$

where I is the current due to 100 000 kVA at 400 volts, i e., 144 000 amperes, and

$$If = \frac{3 \cdot 144\,000 \cdot 100}{1\,503} = 28\,800 \text{ amperes}$$

Thus for a fault to earth at a point close up to the 400 volt busbar we have the condition shown in Fig. 4-15.

This condition again ignores any earth resistance either at the ground plate or in the earth path and further it does not take account of the sequence impedances of the 400 volt cable between the transformer and the switchgear. If this is of any length, the reduction due to this cable might be appreciable and, as in the calculations for three phase faults at the lower voltages,

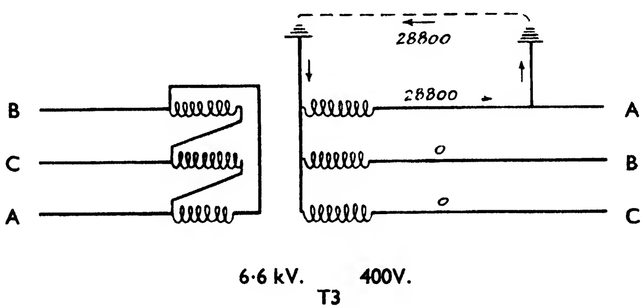


FIG 4-15.

demonstrated in Chapter III, the inclusion on this cable should be considered.

In passing it can be noted that had we been seeking the current for a line to line fault, the result would have been:—

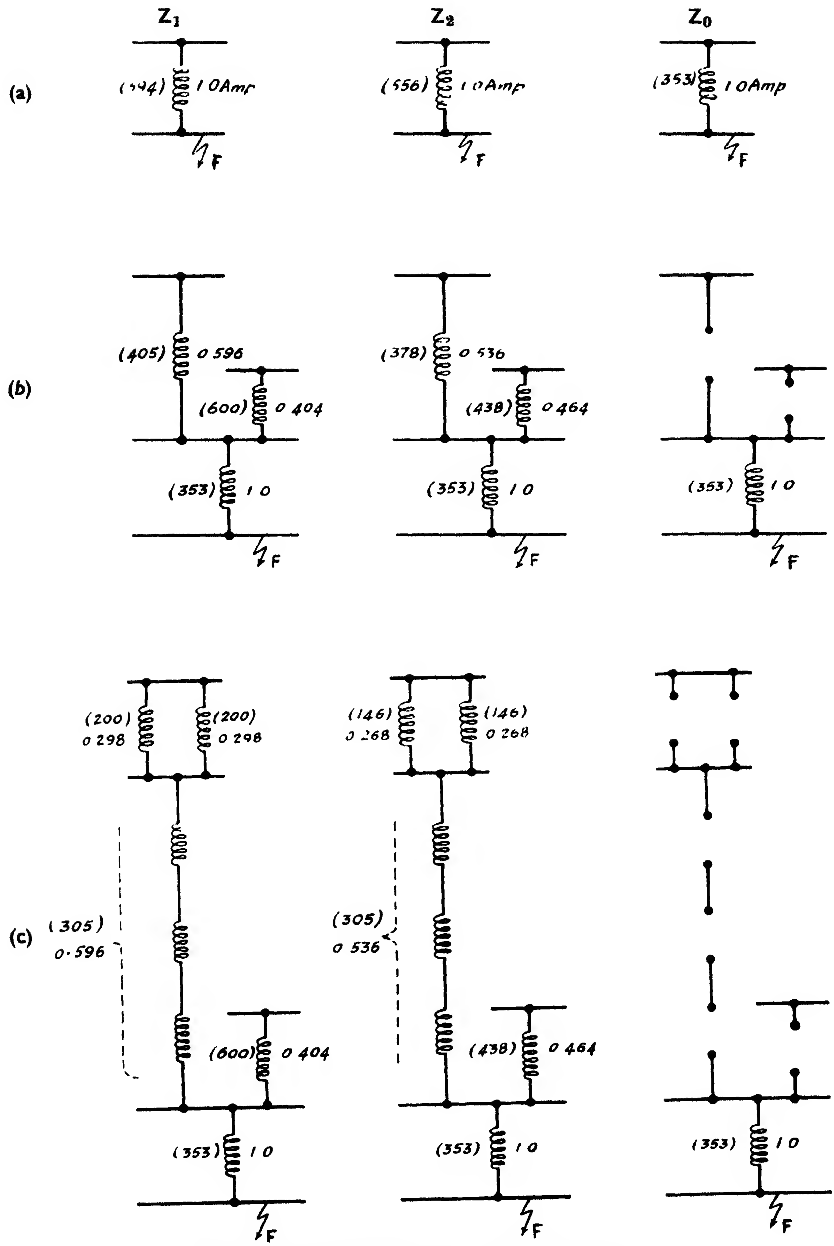
$$If = \frac{\sqrt{3} \cdot I \cdot 100}{Z_1 + Z_2} = \frac{\sqrt{3} \cdot 144\,000 \cdot 100}{594 + 556}$$

$$= 21\,700 \text{ amperes}$$

or for a three phase fault:—

$$If = \frac{I \cdot 100}{Z_1} = \frac{144\,000 \cdot 100}{594} = 24\,200 \text{ amperes.}$$

In order to determine the distribution of current throughout the complete network it is convenient to adopt a method suggested by Wagner and Evans where the reactance diagrams (Figs. 4-11 to 4-14) are worked through in a reverse order, and assuming a figure of one ampere at the fault determine the proportions of this in other branches of the network in inverse proportion to the reactances. The three sequences are placed side



FIGURES IN BRACKETS ARE REACTANCES

FIG 4-16.

by side and Fig. 4-16 shows the stages of calculation. Figures in brackets are reactance values; the other figures being current values in terms of one ampere at the fault. At this stage, it will be noted that all values of current are in terms of the 400 volt star base voltage. Correction for voltage and star/delta transformation will be made later. We have seen that the total fault current If can be split into its sequence values as follows:—

$$If_1 = If_2 = If_0 = If/3 = 28\,800/3 = 9\,600 \text{ amperes.}$$

This value is then equal to our one ampere in Fig. 4-16 (*c*), and by using the factors throughout the remainder of the network we obtain the current distribution on the 400 volt base. This will be clear from Fig. 4-17, where, on the left, are shown the factors (taken from Fig. 4-16 (*c*)) and on the right the current values obtained by using these factors applied to the total current in each phase sequence, *i.e.*, 9 600 amperes. These values are, of course, those in line A, the faulted line. Adding the values given in Fig. 4-17 for I_1, I_2 and I_0, we get the total currents in line A throughout the network, the result being Fig. 4-18. It remains now to determine values for lines B and C, and using formula previously given we get,

LINES B AND C (GENERATORS G1 AND G2).

$$\begin{aligned} I_B &= I_0 + a^2 I_1 + a I_2 \\ &= I_0 + I_1(-0{\cdot}5 - j0{\cdot}866) + I_2(-0{\cdot}5 + j0{\cdot}866) \\ &= I_0 - 0{\cdot}5\,(I_1 + I_2) - j0{\cdot}866\,(I_1 - I_2) \\ &= 0 - 0{\cdot}5\,(2\,865 + 2\,575) - j0{\cdot}866\,(2\,865 - 2\,575) \\ &= -2\,720 - j251{\cdot}5 \end{aligned}$$

$$\begin{aligned} I_C &= I_0 + a I_1 + a^2 I_2 \\ &= -2\,720 + j251{\cdot}5 \end{aligned}$$

These are the values for *each* generator.

LINES B AND C (PRIMARY TRANSFORMER T1).

I_B and I_C here will be the addition of the values for the two generators G1 and G2.

LINES B AND C (SECONDARY TRANSFORMER T1 AND SECONDARY TRANSFORMER T2).

As we are still working on our common base, these values will be the same as for the primary of T1.

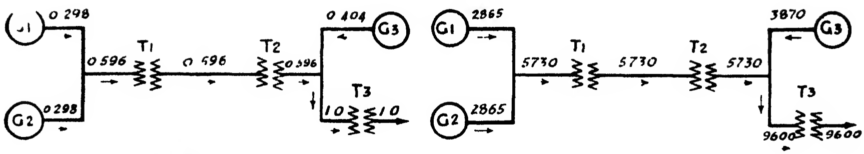
LINES B AND C (GENERATOR G3).

$$\begin{aligned} I_B &= I_0 + a^2 I_1 + a I_2 \\ &= -4\,160 + j503 \end{aligned}$$

$$\begin{aligned} I_C &= I_0 + a I_1 + a^2 I_2 \\ &= -4\,160 - j503 \end{aligned}$$

LINES B AND C (PRIMARY TRANSFORMER T3).

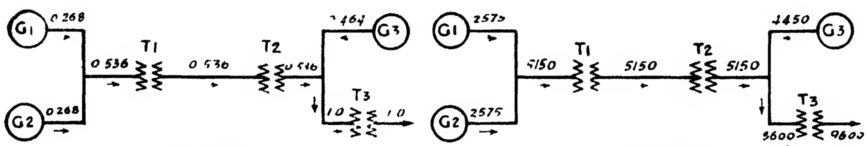
The values here will be the addition of the secondary currents from T2 and the current from G3.



FACTORS CURRENTS

I_1=POSITIVE PHASE SEQUENCE CURRENT—LINE A.

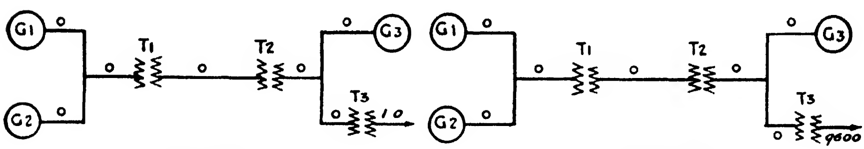
(*a*)



FACTORS CURRENTS

I_2=NEGATIVE PHASE SEQUENCE CURRENT—LINE A.

(*b*)

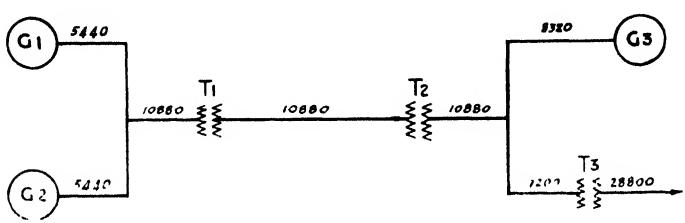


FACTORS CURRENTS

I_0 ZERO PHASE SEQUENCE CURRENT—LINE A.

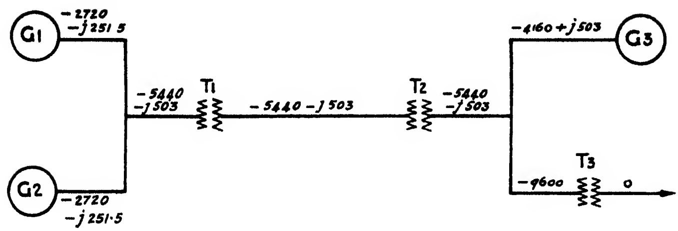
(*c*)

FIG 4-17.



TOTAL FAULT CURRENTS IN LINE A ON 400 VOLT STAR BASE, AND BEING THE SUM OF THE VALUES $I_1+I_2+I_0$ FIG. 4-17

FIG. 4-18.



TOTAL FAULT CURRENTS IN LINE B ON 400 VOLT STAR BASE.

FIG. 4-19.

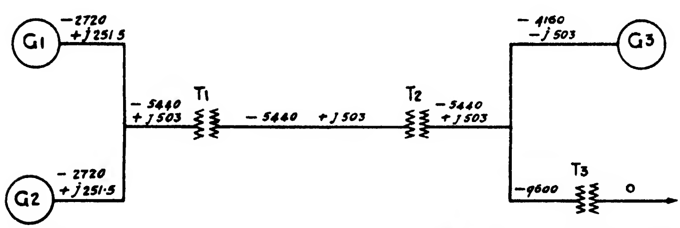
The values so obtained can now be set down as in Figs. 4-19 and 4-20 for lines B and C respectively. It remains only to ascertain the currents at the normal voltages, taking into account star/delta transformation, using the equations on page 85. Starting from the fault, and working backwards.

PRIMARY LINES T3.

$$\text{Line A} = -\frac{231}{6\,600}.(0-0) = 0 \text{ amperes}$$

$$\text{Line B} = -\frac{231}{6\,600}.(0-28\,800) = 1\,010 \text{ amperes}$$

$$\text{Line C} = -\frac{231}{6\,600}.(28\,800-0) = -1\,010 \text{ amperes.}$$



TOTAL FAULT CURRENTS IN LINE C ON 400 VOLT STAR BASE.

FIG. 4-20.

SECONDARY LINES T2 AND LINES G3.

The current in these lines is at the same voltage as the primary lines of T3. Therefore the values for the latter will be divided in the proportion 8 320/19 200 for the generator G3 and 10 880/19 200 for T3. Thus,

$$\text{Line A G3} = \frac{8\,320}{19\,200}.\ 0 = 0 \text{ amperes}$$

$$\text{Line B G3} = \frac{8\,320}{19\,200}.1\,010 = 438 \text{ amperes}$$

$$\text{Line C G3} = \frac{8\,320}{19\,200}.-1\,010 = -438 \text{ amperes}$$

and by subtraction (G3 from T3) we get

SECONDARY LINES T2.

Line A=0 amperes
Line B=1 010−438=572 amperes
Line C=−1 010−(−438)=−572 amperes.

PRIMARY LINES T2, converting from secondary currents T2.

$$\text{Line A}=-\frac{3\ 810}{33\ 000}[572-(-572)]=-132 \text{ amperes}$$

$$\text{Line B}=-\frac{3\ 810}{33\ 000}(-572-0)=66 \text{ amperes}$$

$$\text{Line C}=-\frac{3\ 810}{33\ 000}(0-572)=66 \text{ amperes.}$$

PRIMARY LINES T1, converting from primary currents T2.

$$\text{Line A}=-\frac{19\ 050}{6\ 600}(66-66)=0 \text{ amperes}$$

$$\text{Line B}=-\frac{19\ 050}{6\ 600}[66-(-132)]=-572 \text{ amperes}$$

$$\text{Line C}=-\frac{19\ 050}{6\ 600}(-132-66)=572 \text{ amperes.}$$

GENERATORS G1 AND G2.

The currents here will be one-half of those in the primary lines of T1:—

Line A=0 amperes
Line B=−286 amperes
Line C=286 amperes.

We are now able to construct a diagram of the complete network to show the magnitude and direction of current at each point due to an earth fault at a point just beyond the transformer T3. The diagram is shown in Fig. 4-21.

The calculations could, with equal facility, be carried out using ohmic values instead of percentage. In this case (and as previously indicated) a voltage base is chosen instead of a kVA base. Taking the example in Fig. 4-10, it is convenient to take as a base the voltage at the fault, *i.e.*, 400 volts and the following will indicate the procedure for calculating the fault current to earth.

G1 OR G2 (10 000 kVA 6·6 kV 20% REACTANCE).

Full load normal current=876 amperes

$$\text{Reactance to neutral}=j\frac{20}{100}\cdot\frac{3\ 810}{876}=j0{\cdot}87 \text{ ohms}$$

Referred to 400 volt star base

$$\text{Reactance to neutral}=j0{\cdot}87\left(\frac{231}{3\ 810}\right)^2=j0{\cdot}0032 \text{ ohms.}$$

Thus, $Z_1=j0{\cdot}0032$ ohms

$Z_2=0{\cdot}73Z_1=j0{\cdot}002335$ ohms.

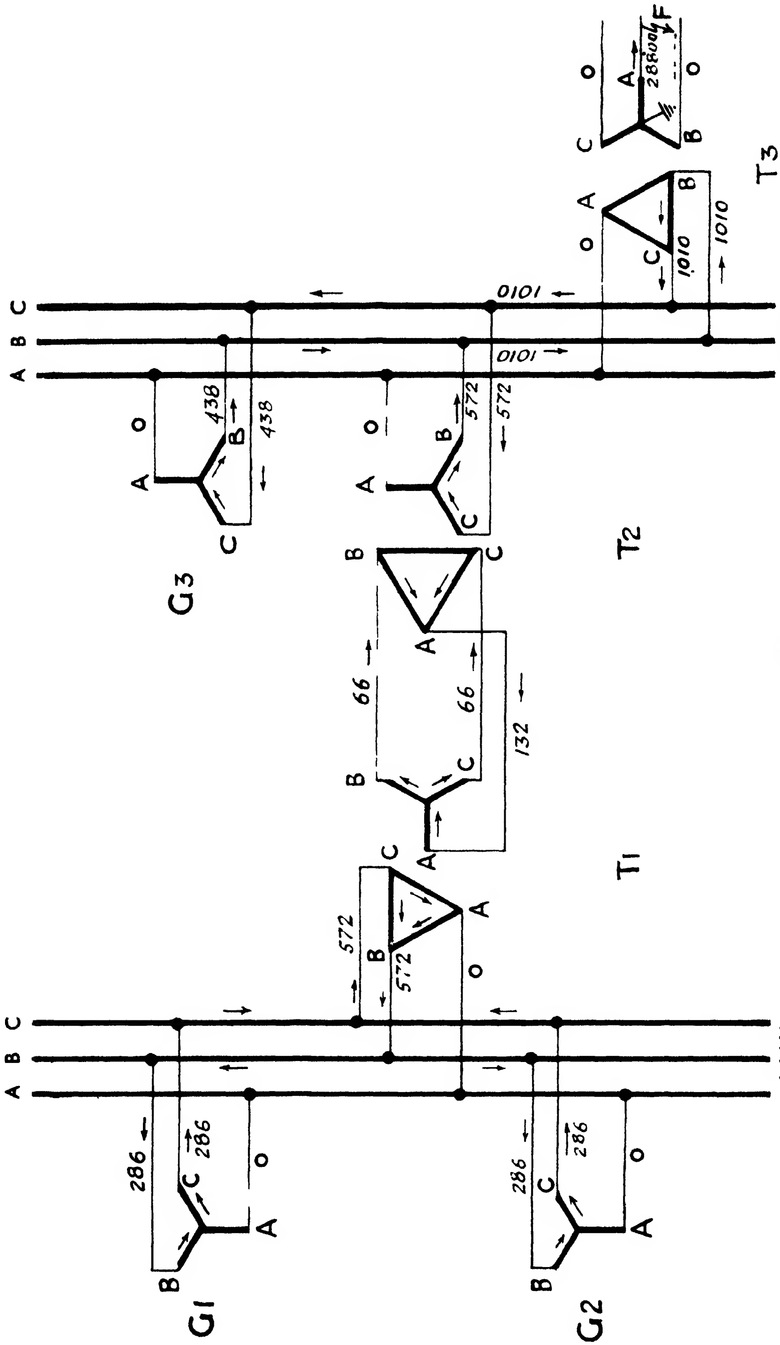

G1
G2
G3
T1
T2
T3
6·6 kV
6·6 kV
33 kV
400 V
286
572
66
132
438
1010
28600
F

FIG. 4-21.

T1 OR T2 (5 000 kVA 6·8% REACTANCE T1 AT 6·6 kV, T2 AT 33 kV).

Full load normal current T1=438 amperes at 6·6 kV
Full load normal current T2=87·5 amperes at 33 kV

Reactance to neutral T1 $= j\dfrac{6\cdot8}{100}\cdot\dfrac{3\,810}{438}$

$= j0\cdot592$ ohms

Reactance to neutral T2 $= j\dfrac{6\cdot8}{100}\cdot\dfrac{19\,050}{87\cdot5}$

$= j14\cdot8$ ohms

Referred to 400 volt star base

$$T1 = j0\cdot592\left(\frac{231}{3\,810}\right)^2 = j0\cdot00218 \text{ ohms.}$$

$$T2 = j14\cdot8\left(\frac{231}{19\,050}\right)^2 = j0\cdot00218 \text{ ohms.}$$

Thus, $Z_1 = Z_2 = j0\cdot00218$ ohms for T1 or T2.

G3 (2 000 kVA 6·6 kV 12% REACTANCE)

Full load normal current=175 amperes

Reactance to neutral $= j\dfrac{12}{100}\cdot\dfrac{3\,810}{175} = j2\cdot61$ ohms

Referred to 400 volt star base

Reactance to neutral $= j2\cdot61\left(\dfrac{231}{3\,810}\right)^2 = j0\cdot0096$ ohms

Thus, $Z_1 = j0\cdot0096$ ohms
$Z_2 = 0\cdot73Z_1 = j0\cdot007$ ohms

T3 (1 500 kVA 6·6 kV 5 3% REACTANCE)

Full load normal current=131·3 amperes

Reactance to neutral $= j\dfrac{5\cdot3}{100}\cdot\dfrac{3\,810}{131\,3} = j1\cdot535$ ohms

Referred to 400 volt Star base

Reactance to neutral $= j1\cdot535\left(\dfrac{231}{3\,810}\right)^2 = j0\cdot00565$ ohms

Thus $Z_1 = Z_2 = Z_0 = j0\ 00565$ ohms

OVERHEAD LINE (33 kV)

Reactance to neutral $= j3\cdot6$ ohms

Referred to 400 volt Star base

Reactance to neutral $= j3\cdot6\left(\dfrac{231}{19\,050}\right)^2 = j0\cdot00053$ ohms

Thus $Z_1 = Z_2 = j0\cdot00053$ ohms

Proceeding now as described earlier, a series of network reduction diagrams (Figs. 4-22, 4-23 and 4-24) will result in the ascertainment of a single equivalent reactance for each of the phase sequences.

We now have:—

$$Zt = Z_1 + Z_2 + Z_0$$
$$= j0{\cdot}00952 + j0{\cdot}0089 + j0{\cdot}00565$$
$$= j0{\cdot}02407 \text{ ohms.}$$

The total earth fault current is then:—

$$If = \frac{3\,E}{Zt} = \frac{3{\cdot}231}{0{\cdot}02407} = 28\,800 \text{ amperes}$$

exactly as calculated by the percentage reactance method. Current distribution calculation will be as before.

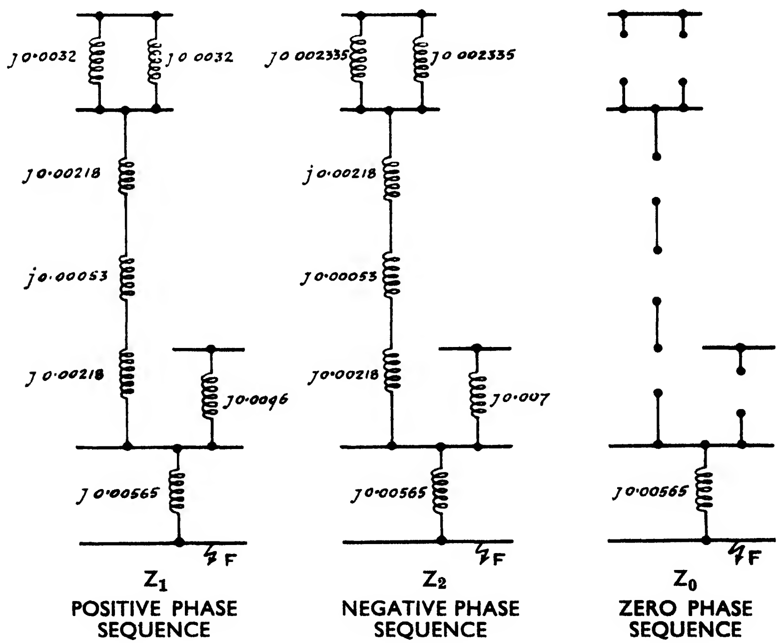


FIG. 4-22.

It is of interest here to note that where there are two reactances in parallel, current distribution is determined as follows:—

$$I_A = \frac{Z_Y}{Z_X + Z_Y}\cdot It$$

$$I_B = \frac{Z_X}{Z_X + Z_Y}\cdot It$$

where Fig. 4-25 represents the conditions.

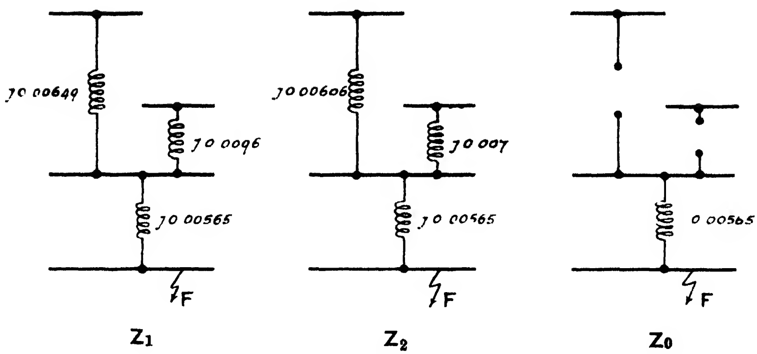


FIG. 4-23

Where, as previously demonstrated, a delta/star conversion is undertaken, it is necessary when determining current distribution in the network to work backwards. For example, the reactance reduction procedure might be as shown at Fig. 4-26 where a delta/star conversion occurs from (*a*) to (*b*).

Working backwards for current distribution we have Fig. 4-27, working from (*e*) to (*a*) and at (*b*) we have currents in a star to be converted to distribution in the delta network at (*a*). This conversion is carried out by making use of the fact that the voltage difference between any two terminals of the delta group is the voltage difference between the two corresponding terminals of the star group. These voltage differences may be determined from the current distribution and reactances of the star group. Having found the voltage difference it is divided by the corresponding delta impedance, giving the current distribution in the equivalent branch of the delta group. Fig. 4-28 illustrates this where at (1) we have the delta/star conversion of reactances and at (2) the star/delta conversion for current distribution, the latter determined as follows:–

Voltage difference A to F (Fig. 4-28)

$$=(1{\cdot}0.j2{\cdot}33)+(0{\cdot}504.j1{\cdot}66)\quad j3{\cdot}167 \text{ volts.}$$

Current distribution

$$\frac{j3{\cdot}167}{j6}=0{\cdot}528 \text{ amperes.}$$

The other two branches of the delta may be similarly calculated.

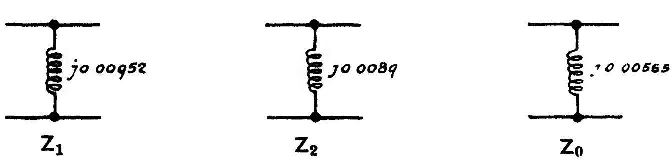


FIG. 4-24.

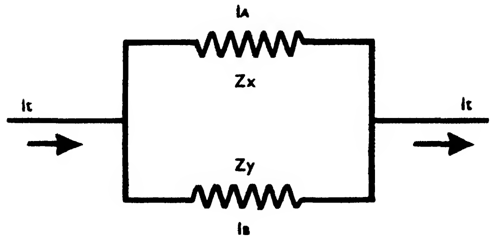
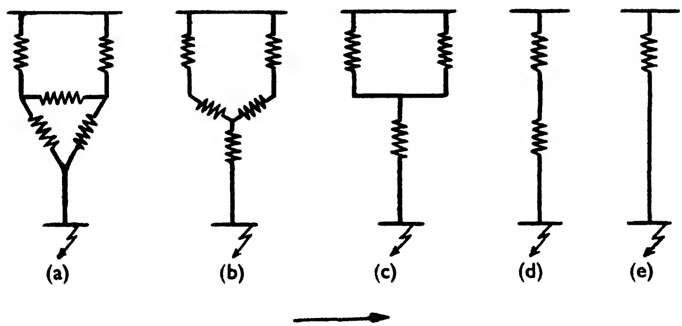
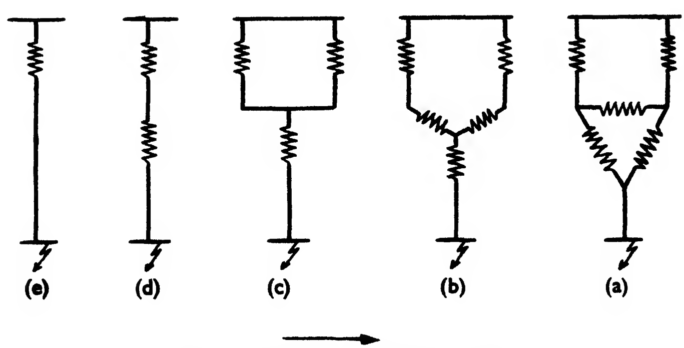


FIG. 4-25



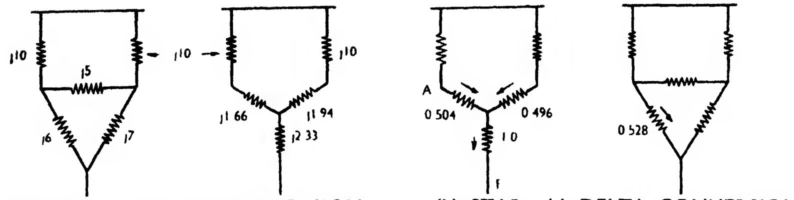
CIRCUIT IMPEDANCE REDUCTION

FIG 4-26



UNIT CURRENT DISTRIBUTION

FIG. 4-27.



(a) DELTA (b) STAR CONVERSION (b) STAR (a) DELTA CONVERSION
1. IMPEDANCES 2. UNIT CURRENT DISTRIBUTION

FIG. 4-28.

BIBLIOGRAPHY

Circuit Analysis of A.C. Power Systems, Vol. I, Edith Clarke (John Wiley and Sons).

Elements of Symmetrical Component Theory, G. W. Stubbings (Pitman and Sons).

Relay Systems, I. T. Monseth and P. H. Robinson (McGraw, Hill Publishing Co.).

Symmetrical Components as applied to the Analysis of Unbalanced Electrical Circuits, C. F. Wagner and R. D. Evans (McGraw, Hill Publishing Co.).

The Calculation of Unsymmetrical Short-Circuits, H. Rissik (Pitman and Sons).

The J. & P. Transformer Book, S. Austen Stigant and H. Morgan Lacey and A. C. Franklin (Johnson and Phillips, Ltd.).

"DECREMENT CURVES FOR POWER SYSTEMS," G. F. Dalziel, "Trans. A.I.E.E.," 1934, Vol. 53.

"EARTH FAULTS—ANALYSIS BY METHOD OF PHASE SEQUENCE COMPONENTS," G. A. Robertson, "The Electrician," July 20, 1934 to May 10, 1935.

"EVALUATION OF FAULT CURRENTS AND VOLTAGES," J. R. Mortlock, "B.T.H. Activities," April, 1941 and July, 1941.

"SYMMETRICAL COMPONENTS—THEIR THEORY AND APPLICATION," E. A. Reeves, "The Electrician" 9th-30th November, 1951.

"SYMMETRICAL COMPONENTS—NOTES ON THEIR PRACTICAL APPLICATIONS," K. W. Wardrop, "The Electrician" 9th September, 1949.

"THE MANAGEMENT OF PROTECTIVE GEAR ON POWER SUPPLY SYSTEMS," W. Casson and F. H. Birch, "Journal I.E.E.," Vol. 89, Part II, No. 10, August, 1942.

"THE METHOD OF SYMMETRICAL CO-ORDINATES APPLIED TO THE SOLUTION OF POLYPHASE NETWORKS," C. Le G. Fortescue, "Transactions A.I.E.E.," 1918, Vol. 37.

CHAPTER V

SHORT-CIRCUIT TESTING OF CIRCUIT INTERRUPTING DEVICES

CHAPTER V

SHORT-CIRCUIT TESTING OF CIRCUIT INTERRUPTING DEVICES

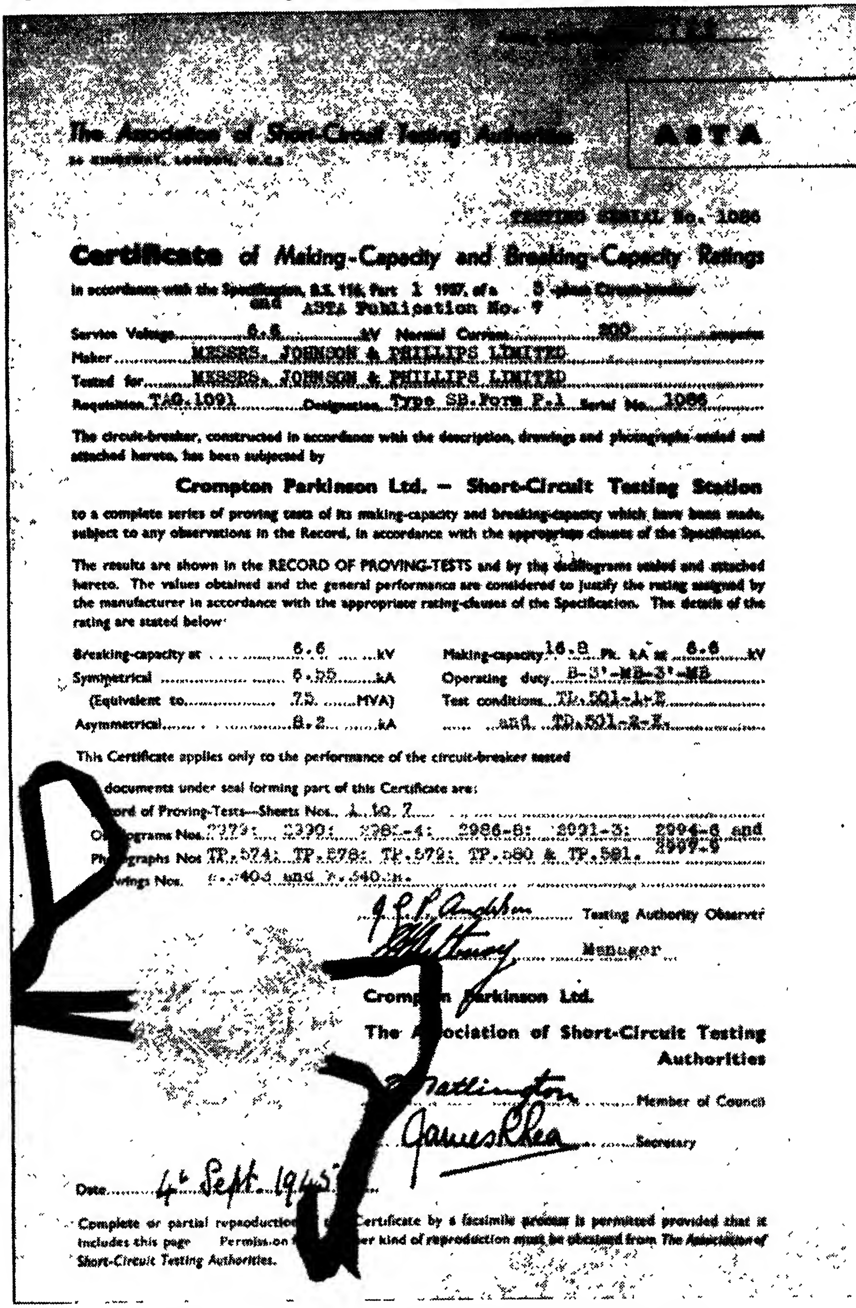
We have discussed, in Chapter II, the principles of circuit interruption and in Chapters III and IV have shown how calculations can be made to ascertain the values of short-circuit which may have to be interrupted under fault conditions. In this chapter we shall be concerned to consider the facilities and procedure necessary to prove that an interrupting device will in fact perform satisfactorily within the short-circuit ratings assigned to it by the manufacturer. Service conditions impose many varied duties on circuit-breakers and fuses and it is essential that the proving tests made are comprehensive to cover all foreseeable circumstances.

The first essential then is to have available the facilities for testing a range of apparatus under actual short-circuit conditions, with means of close control of the many factors which must be observed, e.g. current, voltage, power factor, recovery and restriking voltages and others, and with specialised measuring and recording equipment.

Before considering the basic requirements of such plant, it is of interest to record, briefly, the historical background to the establishment of short-circuit test plants in Great Britain, going back to the 1920's. In those days the short-circuit rating assigned to any interrupting device depended largely on the behaviour of similar devices in service, on the interpretation of certain empirical formulae advocated by various investigators, by such tests as could be carried out on commercial alternators when these were undergoing other routine tests prior to despatch, or, in the case of h.r.c. fuses, on heavy current d.c. tests derived from batteries. In addition, the results of early researches by the E.R.A. on the fundamentals of arc interruption were studied and applied; but with all this, it was rarely ever possible to give any recorded proof of performance and much had to be taken for granted.

The need for the establishment of adequate proving facilities and for the acceptance of standard specifications against which proving tests could be carried out was first urged in the 1920's, particularly by the late H. W. Clothier who campaigned for a national plant under an accredited authority. Co-operative action of this nature was not forthcoming and in 1929 independent action on the part of Messrs. A. Reyrolle & Co. Ltd., led to the establishment of the first short-circuit testing station in Great Britain at Hebburn, Co. Durham. Today there are a number of plants in operation all belonging to manufacturers and it is now the rule rather than the exception for all interrupting devices to be proved and certified to a specified rating in accordance with a testing routine as laid down in the relevant British Standard or to agreed rules in amplification, or pending the issue, of such standards.

The failure to establish a national plant by co-operative effort has to some extent been offset by the linking up of eight British plants in the



The Association of Short-Circuit Testing Authorities

ASTA

PROVING SERIAL No. 1086

Certificate of Making-Capacity and Breaking-Capacity Ratings

in accordance with the Specification, B.S. 116, Part 1 1937, of a 3-phase Circuit-breaker and ASTA Publication No. 7

Service Voltage 6.6 kV Normal Current 800 amperes

Maker MESSRS. JOHNSON & PHILLIPS LIMITED

Tested for MESSRS. JOHNSON & PHILLIPS LIMITED

Requisition TAG.1091 Designation Type SB.Form P.1 Serial No. 1086

The circuit-breaker, constructed in accordance with the description, drawings and photographs sealed and attached hereto, has been subjected by

Crompton Parkinson Ltd. – Short-Circuit Testing Station

to a complete series of proving tests of its making-capacity and breaking-capacity which have been made, subject to any observations in the Record, in accordance with the appropriate clauses of the Specification.

The results are shown in the RECORD OF PROVING-TESTS and by the oscillograms sealed and attached hereto. The values obtained and the general performance are considered to justify the rating assigned by the manufacturer in accordance with the appropriate rating-clauses of the Specification. The details of the rating are stated below:

Breaking-capacity at 6.6 kV	Making-capacity 16.8 Pk. kA at 6.6 kV
Symmetrical 6.55 kA	Operating duty B-3'-MB-3'-MB
(Equivalent to 75 MVA)	Test conditions TD.501-1+2
Asymmetrical 8.2 kA	and TD.501-2-2

This Certificate applies only to the performance of the circuit-breaker tested

documents under seal forming part of this Certificate are:

ord of Proving-Tests—Sheets Nos. 1 to 7

O grams Nos. 2379; 2390; 2982-4; 2986-8; 2991-3; 2994-6 and 2997-9

Ph graphs Nos TP.574; TP.578; TP.579; TP.580 & TP.581.

wings Nos. 404 and 540

Testing Authority Observer

Manager

Cromp n Parkinson Ltd.

The ociation of Short-Circuit Testing Authorities

Member of Council

Secretary

Date 4th Sept. 1945

Complete or partial reproduction of this Certificate by a facsimile process is permitted provided that it includes this page. Permission for any other kind of reproduction must be obtained from The Association of Short-Circuit Testing Authorities.

FIG. 5-1.—*Typical A.S.T.A. certificate of rating.*

N.V. tot Keuring van Electrotechnische Materialen

TELEFOON 33133* ARNHEM UTRECHTSEWEG 310

CERTIFICATE OF RATING N°. 4782 - 59

CLIENT Messrs. Johnson & Phillips Ltd., Charlton, London, England.
MANUFACTURER Messrs. Johnson & Phillips Ltd., Charlton, London, England.
APPARATUS TESTED a three phase oil circuit breaker, fitted with OM2/EC4 operating mechanism for 350 MVA/11kV
11kV 800 A 3- phase designated as PDB (Mark 1) Serial no --
constructed in accordance with the drawings and photographs sealed and attached hereto

The tests have been made in accordance with British Standard 116:1952 clauses 49 and 58.

The performance of the apparatus tested and observations made during the tests have been recorded in the Schedules of Test Results and Oscillograms

THE DOCUMENTS CONSTITUTING THIS REPORT ARE

Schedule of Test Results-Sheets Nos 5 to 14 incl.
Drawings Nos W.5901007/2
Photographs Nos 310343, 310346, 310348, 310354, 310355, 310356, 310357.
Diagrams Nos --
Electro-magnetic-oscillograms Nos 590601 - 02 05 06,07,16,17,24,25,26,27,28,29,30,31, 32,33.
590602 - 02,03,04,08 09,10,11 12,13,14,15,16.
590603 - 04.
590605 - 28,29 30,31.

Cathode ray oscillograms Nos --

TESTS

No load timing tests

Test No. 590601	- 02	Break test
Test No. 590601	- 16,17	Make tests
Test No. 590601	- 24	Make - break test
Test No. 590602	- 02,03,04	Make tests.

Break tests at 11 kV

Test No. 590601	- 05,06,07	Testduty 5 with 18.4 kA and 23 0 kA asym.
Test No. 590601	- 25,26,27	Testduty 3 with 11.0 kA
Test No. 590601	- 28,29,30	Testduty 2 with 5.50 kA
Test No. 590601	- 31,32,33	Testduty 1 with 1,84 kA
Test No. 590602	- 08	Testduty 4 with 18.4 kA
Test No. 590602	- 11,12,13	Tests with 0.913 kA
Test No 590602	- 14,15,16	Tests with 0.457 kA

Make- Breaktests at 11 kV

Test No. 590602 - 09,10 Testduty 4 with 46.8 kA_{peak} and 18.4 kA

Through current tests

...st No. 590603 - 04 Test with 47.5 kA_{peak} and 19.1 kA during 3.03 sec.

Single phase tests at 9.5 kV

...est No. 590605 - 28 Test with 18.4 kA Red phase
...st No. 590605 - 29,30 Tests with 18.7 kA. Yellow Phase
...est No. 590605 - 31 Test with 18.5 kA. Blue phase.

...he values obtained and the general performance are considered to justify the rating assigned by the manufacturer.
The details of the rating are stated below:

...eaking capacity at 11 kV Making capacity 46.8 kA_{peak} at 11 kV
...metrical 18.4 kA
...valent to 350MVA Shorttime current capacity 18.4 kA for 3.0 seconds.
...etrical 23.0 kA
...ng duty: B - 3[1] - MB - 3[1] - MB

NV KEMA

ARNHEM, 3rd February 196...

(Manager)

Fig. 5-2.—*Typical K.E.M.A. certificate of rating.*

Association of Short-Circuit Testing Authorities, better known by its abbreviated title A.S.T.A.

Plants similar to those in Great Britain exist in many parts of the world, some belonging to manufacturing firms and others, such as that of K.E.M.A.* at Arnhem and C.E.S.I.† at Milan, being co-operative organisations sponsored by Government Departments, Electricity Supply Undertakings, Manufacturers and Research Institutions. Organisations of this type embrace many other research and test laboratories, the short-circuit test plant being but one section of the whole. British short-circuit test plants on the other hand confine themselves largely to such testing and research leaving other work such as impulse testing, network studies, atmospheric testing and material specifications, to other separate laboratories.

To establish a short-circuit test plant is an exceedingly costly project and there are many switchgear and fuse manufacturers to whom the cost of providing their own facilities is prohibitive. Some of these manufacturers have, nevertheless, established relatively small plants designed specially for the testing of a particular product, e.g. contactors where the high powers associated with circuit-breakers do not arise.

The facilities of A.S.T.A. test plants have therefore been made available, by agreement, to non-owners so that apparatus may be submitted to test up to the limits of 33 kV and 750 MVA‡. The facilities of K.E.M.A. and C.E.S.I. are equally available and both these authorities undertake tests strictly in accord with British and International Standards.

Apparatus which passes the tests successfully is granted a certificate of rating coupled with a full report of performance and such certificates may be quoted by the manufacturer in justification of his assigned ratings Typical certificates as issued by A.S.T.A. and K.E.M.A. are shown in Figs. 5-1 and 5-2.

The stage at which a certificate is obtained for a particular design, however, is only one of many stages which may be involved. There will be the preliminary stages when the development of a new design requires some proof that the basis is sound. This will probably be followed by further tests after modifications have been made either in detail or on a wholesale scale Proof will be necessary that various operating mechanisms (in the case of circuit-breakers) such as hand, spring or solenoid, are adequate for the duty imposed on them under short-circuit conditions, particularly that of closing a breaker onto a fault Apparatus associated with a circuit-breaker or fuse, e.g. busbars, connections, current transformers, must be proved as capable of withstanding the stresses, electromagnetic and thermal, of short-circuit equal to the breaker or fuse rating. Thus, the development of a final commercial product from the early tests to the final certification stage may require the services of a test plant at intervals over a period of many months or even years.

With this background, it is now appropriate to consider the facilities necessary for tests to be carried out. The extent of these will depend very largely on the limits of both voltage and MVA for which the plant is designed. If these limits are those at present recognised for low-voltage h.r.c. fuses

**N.V. tot Keuring van Electrotechnische Materialen.*
†Centro Elettrotecnico Sperimentale Italiano Giacinto Motta.
‡These limitations have now been removed.

or circuit-breakers and/or those for distribution switchgear up to 11 or 22 kV 500-750 MVA, the plant will be very different to that which has to cover all voltages up to 300 or 400 kV and fault values up to, say, 35 000 MVA at the highest level.

To meet the first case a simplified single-line diagram of the plant could well be that shown in Fig. 5-3 but for the second case, the plant would more likely appear something like that in Fig. 5-4, a diagram which shows the present plant of The Switchgear Testing Co. Ltd.*

Perhaps the majority of the world's test plants derive power from motor-driven generators as the diagrams indicate, specially designed and installed for the purpose—this is the case for all British stations. There are some, however, such as the C.E.S.I. plant in Milan, where power is taken

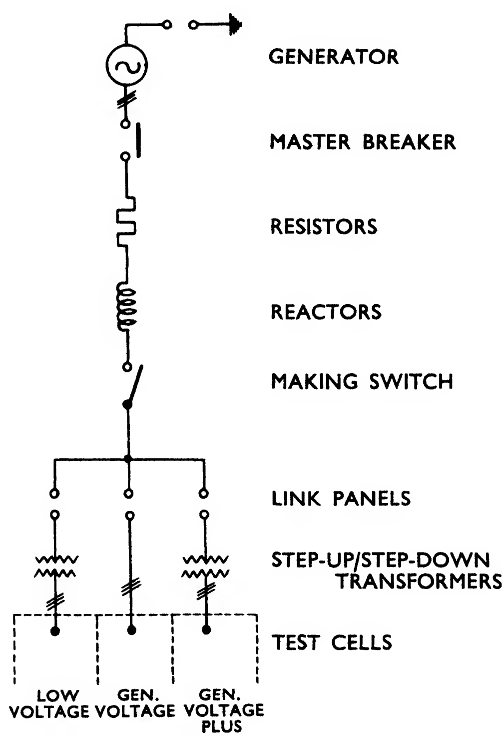


FIG. 5-3.—*Elementary connection diagram for simple test plant.*

from the supply company network i.e. the 220, 23 and 6·4 kV systems of Edisonvolta S.p.A., as shown in simplified form in Fig. 5-5 and omitting all the details of reactors, resistors, master breakers and making switches.

**Operating for the Switchgear Division of Associated Electrical Industries Ltd*

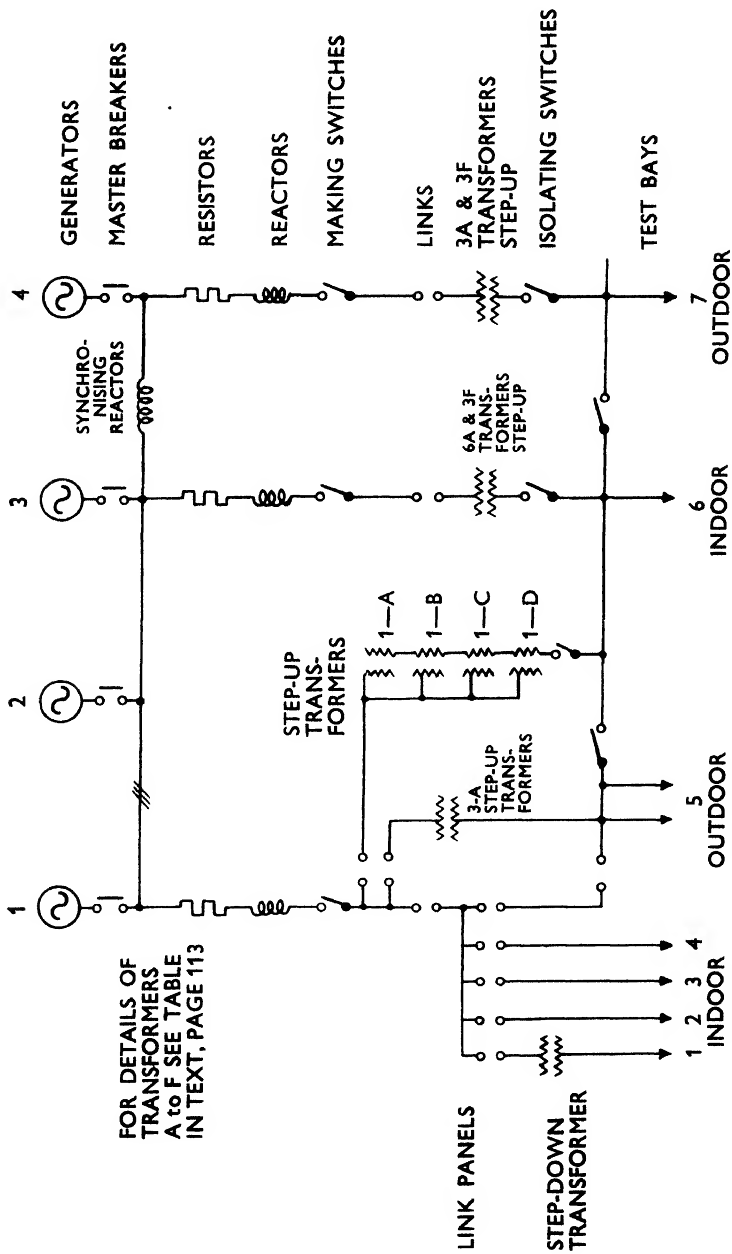


FIG. 5-4.—*Single-line diagram of short-circuit test plant (The Switchgear Testing Co. Ltd.).*

At the K.E.M.A. plant, motor-driven generators are employed as in British stations but a link is provided with the' 150 kV National Grid Networks so that circuit-breakers in certain classes may be tested for line-switching ability.

For the purpose of recording the many values of current, voltage, pressure, travel and other quantities during a test, much ancillary equipment is necessary and an idea of this is noted in Fig. 5-6. All this equipment will be housed in a separate control room from which the tests may be observed by the test plant engineers and visitors.

Nearly every station has some feature of special interest, some in the manner of cascading transformers for the very high voltages, others in the way they provide for high current at a high recovery voltage by either "super-excitation" or "over-excitation", or in the design of some particular piece of apparatus, e.g. the making switch. It would be impossible within the scope of this book to describe the features of the various stations and instead it will satisfy our purpose to give a brief general description of the major items, noting that all are specially designed to meet the requirements of the station. This is particularly the case in regard to components which have to be repeatedly short-circuited, with consequent shock.

The generators are, in external appearance, not unlike those which exist in many power stations, except that they are motor driven. The four machines noted in Fig. 5-4 each have a frame size of 60 MVA and the driving motor is a 1 200 h.p. induction type. Apart from specially braced windings, the stator will have a very low reactance in order to give the maximum short-circuit output in the first cycle. It may be mounted on a resilient base, e.g. springs to minimise the mechanical shock transmitted to the foundation by the short-circuit oscillating torque, and its stator windings will be arranged for connecting up in various ways. In this latter connection, some test generators are arranged so that the stator windings can be connected in star or delta to give nominal voltages of 11 kV and 6·6 kV respectively, while others may have two stator windings per phase and a terminal arrangement such as to permit the windings to be connected in parallel delta or star and series delta or star to give terminal voltages of 6·6, 11·0, 12·7 and 22·0 kV. These figures apply to most of the British stations while the machines at K.E.M.A., again with two stator windings, give voltages of 3·2, 5·5, 6·4 and 11 kV.

Just prior to the short-circuit test the excitation of the generator has to be boosted to maintain the flux and thus diminish the decrement of the short-circuit current, in addition to giving higher values of recovery voltage.

For tests at voltages other than those at any of the available generator voltages (or at C.E.S.I. of the supply network), transformers will be installed. To step-down to lower values a three phase transformer is normal but to step-up to higher voltages, it is more usual to employ banks of single phase units. These transformers are in no way standard types as, in addition to being designed to withstand repeated short-circuits, the windings are often arranged in sections for voltage adjustment and for series or parallel combinations.

In the station shown diagrammatically in Fig. 5-4, there are in all 24 single phase step-up transformers as indicated in Table 5 : 1.

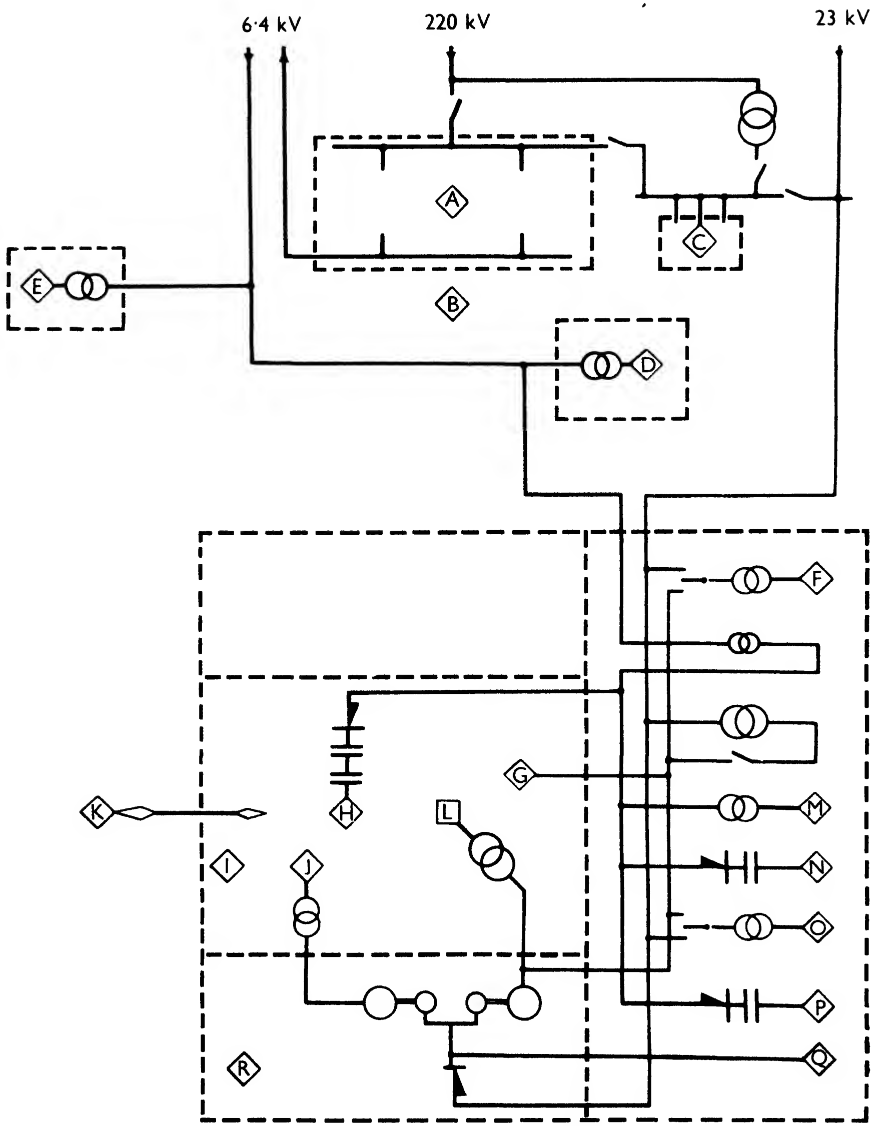


FIG. 5-5.—*Diagram of layout of C.E.S.I. switchgear testing laboratories, Milan (See legend on facing page)*

TABLE 5 : 1

Number	Transformer unit designation (see Fig. 5-4)	Ratio of transformation kV	No. of secondary sections	Insulation level working voltage kV r.m.s. to earth
13	A	6·35/76	12	76
1	B	6·35/57	1	133
2	C	6·35/57	1	190
2	D	6·35/57	1	266
6	F	6·35/76	1	160

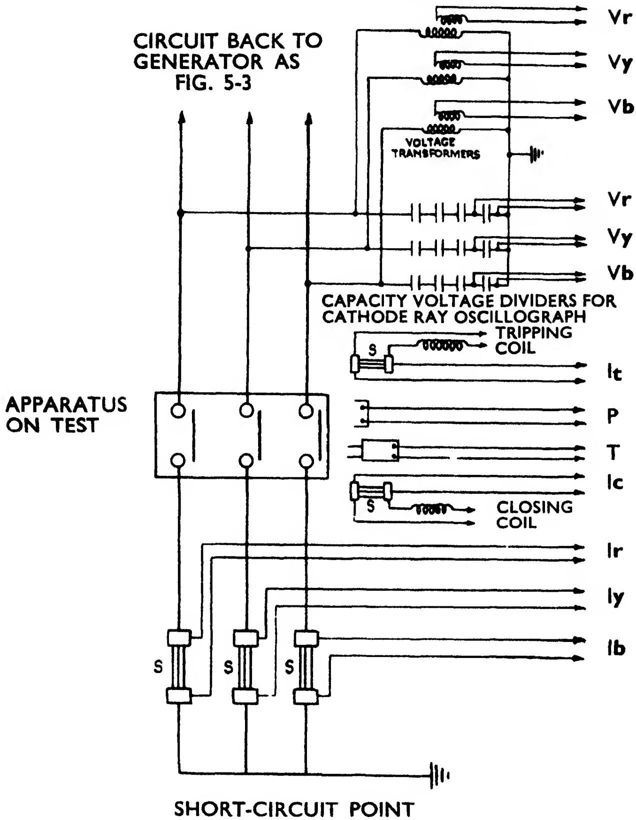
The unit A transformers have each of the 12 secondary sections brought out to a pair of terminals, each section giving 6·35 kV. Any or all of these sections may be used to provide voltage settings corresponding to steps of 11 kV (line to line) up to 132 kV. When connected in series with other transformers (B, C, D or F) the unit A secondary sections are used as a vernier adjustment of total voltage. A few typical circuit arrangements are given in Fig. 5-7.

With the complement of generators and transformers shown in Fig. 5-4, the station can test to the values given in Table 5 : 2

C.E.S.I TEST AND RESEARCH PLANTS:

LEGEND FOR FIG. 5-5

A SHORT-CIRCUIT TESTS AT 50 C.P.S.: 220 kV, 3 000 MVA; 60/150 kV, 2 000 MVA
B NO-LOAD LINE SWITCHING: 60/220 kV, 500 km
C SHORT-CIRCUIT TESTS AT 50 C.P.S.: 5/30 kV, 2 000 MVA
D SHORT-CIRCUIT TESTS AT 50 C.P.S.: 220/380 V, 6 500 A
E STUDIES ON ELECTRIC NETWORKS (A.C. NETWORK ANALYZER)
F SHORT-CIRCUIT TESTS AT 50 C.P.S.: 0·3/1 kV, 260/75 kA
G TEMPERATURE TESTS AT 40/65 C.P.S., 1·7/6 kV, 10 MVA
H IMPULSE VOLTAGE TESTS: 3·6 MV, 300 kJ
I HIGH TENSION WET TESTS
J INDUCED VOLTAGE TESTS AT 300/390 C.P.S., 1·4/60 kV, 4 MVA
K OUTDOOR HIGH TENSION TESTS (ON LINES, CABLES, ETC.)
L DIELECTRIC TESTS AT 40/65 C.P.S., 2 MV, 1 MVA
M HIGH TENSION TESTS AT 50 C.P.S., 200 kV, 60 kVA
N IMPULSE VOLTAGE TESTS: 500 kV, 2 kJ
O DUTY TESTS ON LIGHTNING ARRESTERS: 25 kV, 700 A FOLLOW CURRENT
P IMPULSE VOLTAGE AND CURRENT TESTS, 2·4 MV, 90 kJ; 500 kA
Q DIRECT CURRENT SHORT-CIRCUIT TESTS: 0·75/3·6 kV, 34/17 kA
R MECHANICAL AND HIGH TENSION TESTS UNDER CONTROLLED ATMOSPHERE CONDITIONS



LEGEND

Vr	RED PHASE VOLTAGE
Vy	YELLOW PHASE VOLTAGE
Vb	BLUE PHASE VOLTAGE
It	TRIP COIL CURRENT
P	FLUID PRESSURE
T	TRAVEL RECORDER
Ic	CLOSING COIL CURRENT
Ir	RED PHASE CURRENT
Iy	YELLOW PHASE CURRENT
Ib	BLUE PHASE CURRENT
S	SHUNT

FIG. 5-6 —*Test plant measurement circuits.*

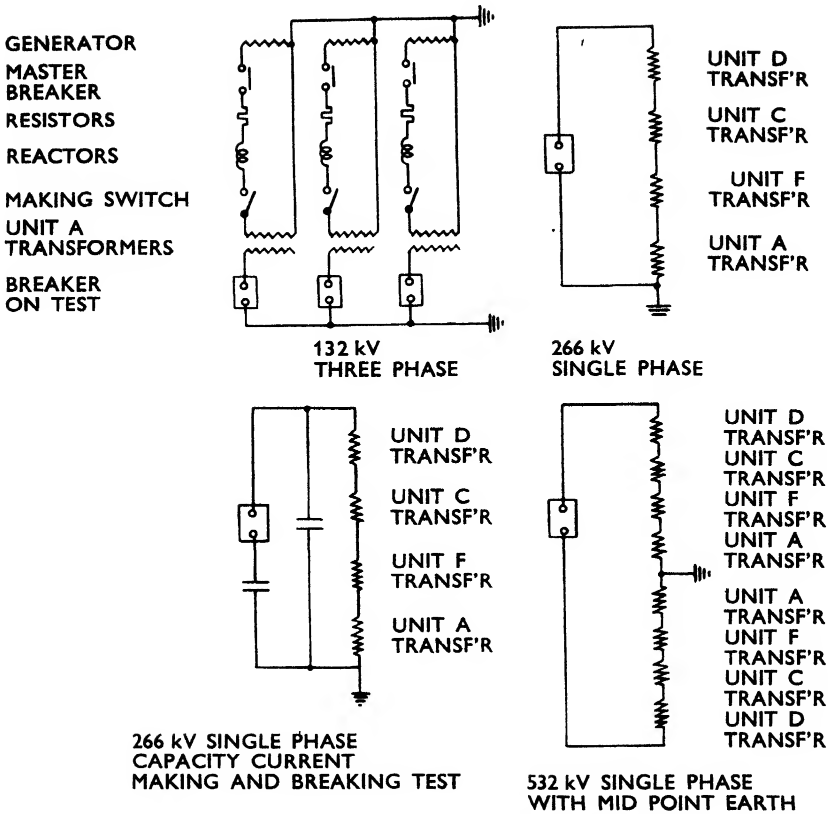


FIG. 5-7.—*Some typical test circuits for the higher voltages showing combinations of single phase transformers from Table 5:1. (In the single phase diagrams only the secondary windings are shown). (The Switchgear Testing Co. Ltd.).*

TABLE 5 : 2

Voltage		MVA
0·415 to 3·3 kV	Three phase	100/300
6·6 to 22 kV	Three phase	1 000/2 800
33 to 132 kV	Three phase	2 400/2 600
275 kV	Three phase	1 600
66 to 600 kV	Single phase	
	(a)	900/4 500
	or (b)	600/3 000

NOTE—The outputs in this table for single phase tests on one pole of a circuit-breaker are expressed as equivalent three phase MVA, those at (a) being for the condition where the recovery voltage is equal to the phase voltage and those at (b) where the recovery voltage, first phase to clear, on a 600 kV system is 520 kV and covered by the 532 kV single phase test connection.

In the K.E.M.A. plant there are two short-circuit test laboratories each of which can operate as a unit or they can be linked when necessary for the higher powers. There are two generators in each laboratory those in one each giving 650 MVA three phase symmetrical and in the other, each giving 1 500 MVA three phase symmetrical. To cover tests at voltages above those available from the generators, 12 single phase transformers are available arranged in four three phase banks. On two of these banks the secondary windings have four sections each giving 12·5 kV, while on the other two banks there are two sections per secondary winding each giving 25 kV. By connecting in series, series parallel or parallel delta and star, a wide selection of voltages up to 100 kV in one laboratory and 220 kV in the other is possible. Tests to the values given in Table 5 : 3 can be undertaken in this station.

TABLE 5 : 3

Voltages		MVA	kA symm.
LABORATORY I			
0·22 to 1·1	Single phase or Three phase		40/80
up to 100 kV	Three phase	750/1 200	
up to 200 kV (mid point earthed)	Single phase (a)	1 300	
LABORATORY II			
0·22 to 1·1	Single phase or Three phase		60/120
up to 173 kV	Three phase	2 500/3 000	
up to 220 kV (to earth)	Single phase (a)	3 600	
LABORATORIES I AND II COMBINED			
up to 220 kV (to earth)	Single phase (a)	5 000	
	(b)	7 500	

NOTE—The outputs given in this table for single phase tests on one pole of a breaker are expressed as equivalent three phase values

(a) are values where the recovery voltage is equal to 1·5 times phase voltage.

(b) are values where the recovery voltage is equal to phase voltage.

Series reactors and resistance banks, as shown in the diagrams, are provided for the regulation of the test current, the reactors being used to adjust the magnitude and the resistors to control the rate of decay of the

d.c. component of current. The value of short-circuit power factor will also be controlled by this means.

In all types of testing, the failure of the apparatus under test is a contingency which must be allowed for. This is particularly the case in the testing of circuit interrupting devices and indeed in some research tests it is normal to continue raising the test values by increments until failure occurs, even to destruction. In such circumstances the short-circuit must be cleared by another circuit-breaker backing up the test piece and in the diagrams this is shown as the master breaker. This, set to open a predetermined time after the initiation of the short-circuit, must be capable of clearing faults up to the highest level of each generator or other power source and have a substantial margin of safety. The master breakers in the station represented by Fig. 5-4 have a breaking capacity of 90 kA symmetrical and 115 kA asymmetrical at 11 kV.

When testing for breaking capacity only, the master circuit-breaker and the breaker to be tested will both be in the closed position and the short-circuit will be applied by closing the "making switch" (see Fig. 5-3). The duty thereby imposed on this switch is very onerous, namely that of making on to the high peak current which occurs in the first half-cycle of short-circuit and reaching, on some tests, over 100 000 amperes. It is important that the speed of closing of this switch be high to avoid pre-arcing as the contacts approach the "touch" position. To further assist in this direction, some making-switch designs have the contacts enclosed in a compressed-air vessel, the air being maintained at about 150 lb. per sq in In certain tests it is necessary that the instant of contact-make on the making-switch be controlled so that it occurs at a particular point of the voltage wave and in this respect very considerable accuracy has been achieved by the application of electronic devices coupled with high-speed closing. When testing a circuit-breaker for making capacity, the making-switch will of course be closed first, along with the master breaker as, for this test, it is necessary that the short-circuit be completed by closing the circuit-breaker on test.

In a test plant for the testing of circuit-breakers of a type used for the control of power transmission lines it is often essential that in addition to the tests at high power, others should be made to assess the ability to make and break the capacity currents associated with the switching of unloaded power transmission lines. For this purpose (and others) a bank of high-voltage capacitor units will be installed, and used to simulate the conditions anticipated in service. In stations with a connection to a supply system of overhead transmission, e.g. C.E.S.I., no-load switching tests can be applied direct (see Fig. 5-5); similar facilities exist for testing under actual service conditions at the Electricité de France testing station at Fontenay.

For testing circuit-breakers other than the largest (usually high-voltage outdoor types) covered bays are provided. These bays are box-shaped structures of reinforced concrete with an open front facing the control and observation rooms. Fire fighting apparatus and fire-proof doors for closing the front opening can be brought into operation in the event of trouble by remote control from the control room.

At a point suitably remote from the test plant and test bays is the control house in which the recording and control equipment necessary for the

purpose in hand is installed. This house is also designed to provide facilities for the safe observation of the tests (both by the station staff and by visiting engineers) together with staff offices, etc.

For the purpose of obtaining data necessary for the test record, the electromagnetic oscillograph is used to provide a measurement of the following quantities:—

(a) The short-circuit current in each phase.
(b) The voltage across each pole of a test piece before, during and after a short-circuit.
(c) Fluid pressure (e.g. in oil circuit breakers).
(d) Travel of the moving contacts.
(e) Current in the closing and trip coil circuits.
(f) Generator voltage.

An example of such a record will be given later.

The electromagnetic oscillograph records the normal-frequency recovery voltage that appears across the terminals of a circuit-breaker after opening on a short-circuit, but it does not record the high-frequency restriking voltage transients, which may have a frequency up to 50 000 cycles per second and which may affect the performance of the circuit-breaker. This transient voltage is discussed in Chapter II and its nature shown in Figs. 2-3 and 2-5. Its measurement demands the use of a high-speed cathode-ray oscillograph, an instrument which may also be used to ascertain the severity of the various test-circuits available on the plant, as determined by their high-frequency characteristics. This involves the making of a large number of special short-circuits during which cathode-ray oscillograms are taken. By the use of a restriking voltage indicator (see Journal I.E.E., Vol. 80, page 460, 1937) it is possible for severity data to be obtained without the necessity of making actual short-circuits, and results agree very closely with those obtained with a cathode-ray oscillograph.

Miscellaneous apparatus available in a test plant will include compressed-air plant, oil storage, pumping and purification equipment and photographic apparatus both still and ciné. In many stations the latter will include equipment for high-speed photography for the study of the arc during the fraction of a second it exists, and such cameras have been developed capable of taking thousands of frames per second.*

Finally, there will be a workshop with facilities for modifying detail parts of the apparatus under test and for repairs as may be necessary

Mention has been made earlier of the existence of short-circuit test stations of a somewhat special nature which have been established to provide proving facilities for a particular piece of apparatus e.g. l.v. h.r.c. fuses, contactors, etc. An example of a plant designed specifically for the testing of fuses is one established originally by W. T. Henley's Telegraph Works Co. Ltd., now the Cable Division of Associated Electrical Industries Limited and here, while the plant follows the general line of much larger plants as discussed, there are a number of features of difference. Firstly it is a single phase plant to satisfy the test conditions of B.S. 88 and can cover all requirements of this specification up to 46 000 amperes r.m.s. prospective, (fuse category AC5) at 250 and 440 volts. The alternator

**See article by Thomas, Roberts and Legg noted in the bibliography.*

(motor driven) gives a nominal voltage of 1 760 volts and is coupled directly to a step-down transformer with the master circuit-breaker between, as shown in Fig. 5-8.

It is important in fuse testing that facilities exist to control the point on the voltage wave at which the short-circuit is made, and B.S. 88 states that in the test for rated breaking capacity the short-circuit must be applied at a *rising* voltage of 50 per cent of the peak value with a tolerance of plus or minus 15 per cent of the peak value. At this station the point on wave control has been achieved with consistent accurate timing with specially designed electronic equipment operating direct from the single-phase test voltage. In this station, too, it will be noted (Fig. 5-8) that the resistance and reactor banks, together with the making switch, are all placed on the output side of the test transformer and not as in Figs. 5-3 and 5-4 on the input side. Placing the resistances and reactors in this way facilitates the adjustment of the test circuit parameters to within fine limits and, in addition, the apparatus can be designed for use at the lower voltage. The test transformer itself is an air-cooled unit designed to withstand a secondary current of 46 000 amperes for two seconds.

This station, like many other British plants, derives its source of motor driving power from the supply network, and in such circumstances some provision must be made to avoid drawing excessive current from the mains at the instant of short-circuit. In some stations, this provision is made by disconnecting the driving motor just before the short-circuit is made. In the station under review, the driving motor is of the slip-ring induction type controlled by a resistance starter. At the start of the short-circuit, this resistance is automatically re-inserted in the rotor circuit, thereby controlling the current taken from the mains, but immediately the test sequence is complete, the resistance is shorted out so that the motor resumes its norma, running condition.

A typical short-circuit test plant designed for proving, in particular, contactors or small circuit-breakers is one established by The Belmos Co. Ltd., and here the test alternator gives a voltage of 440 volts 3 phase and can produce short-circuit currents up to a maximum of 17 000 amperes at 440 volts.

The stator windings can be connected in star or in delta and the alternator is driven up to speed by an induction motor through a V-belt drive and gearing. The rotating mass, consisting of the motor and alternator rotors and gearing, has sufficient kinetic energy stored in the system when running at full speed to ensure very little loss of speed due to momentary short-circuit loading and tests can therefore be carried out in rapid succession. This is a requirement when testing contactors, B.S. 775 specifying 50 operations at 10 second intervals or 100 operations at 3 second intervals, depending on the duty class. Such short intervals between making and breaking tests would be extremely difficult to maintain if at each short-circuit the driving motor was disconnected from the supply and had to be reconnected and brought up to speed again. The driving system in this station has been found to so buffer the effect on the supply system to the motor as to render it unnecessary to disconnect the latter except under special circumstances. For example, the set can give an output of 4 MVA

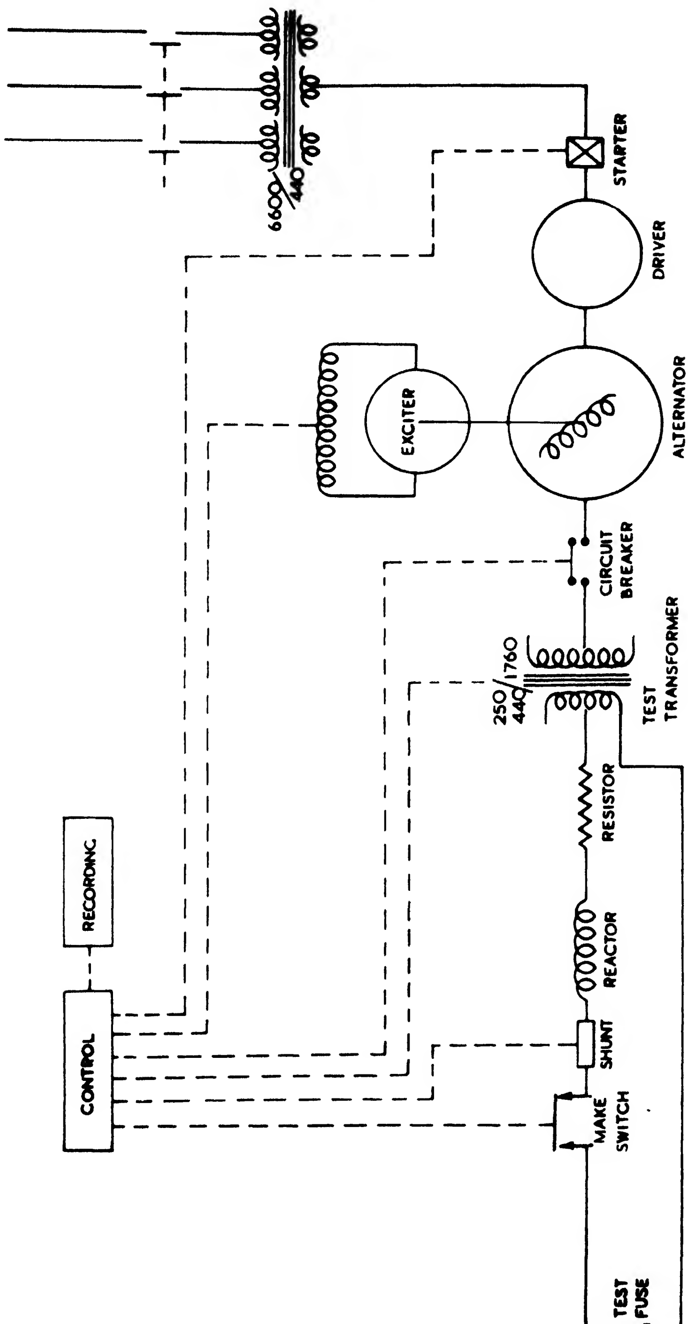


FIG. 5-8.—*Schematic diagram of short-circuit test plant for testing low and medium voltage h.r.c. fuses (Associated Electrical Industries Ltd.—The Henley Short-Circuit Testing Station).*

for five cycles, repeated continuously at three second intervals. This covers a test on 450 ampere contactors at 3 600 amperes, 650 volts, 0·5 p.f.

In a station such as this, when limited to tests at voltages not exceeding 500 or 600 volts, the normal two-winding transformer is not essential and instead an auto-transformer can be used. For tests on 3 300 volt contactors, however, a step-up transformer is necessary.

Having considered the special plant necessary for the short-circuit testing of circuit-interrupting devices, it is appropriate to take brief note of the tests which are necessary to prove the ratings assigned to a particular design. These tests will naturally vary, depending on the device, and it will be obvious that while a circuit breaker must be capable of breaking, making and carrying short-circuit currents, a fuse will largely be concerned only with the breaking duty, and an oil switch, having no automatic protective tripping devices, will be concerned only with breaking normal load currents and making or carrying short-circuit currents. These variations are covered in the standard specifications for the various types of apparatus or, where no specification exists which includes short-circuit test provisions, in sets of rules governing these issued by A.S.T.A., until such time as a standard specification is issued to supersede the rules.

We find therefore that tests recognised in Great Britain will be made in accordance with the undernoted documents—

Oil circuit-breakers	B.S. 116 or B.S. 936
Oil switches	B.S. 2631
Fuses up to 660 V	B.S. 88
Fuses above 660 V	B.S. 2692
Air-break circuit-breakers	A.S.T.A. No. 16
Circuit-breakers and automatic switches in combination with fuses and fuse links	A.S.T.A. No. 22
Unit testing of circuit-breakers for making capacity and breaking capacity	A.S.T.A. No. 15

If we consider, first, the tests necessary to B.S. 116, B.S. 936 and A.S.T.A. No. 16, all covering circuit-breakers, it is noted that two broad differences exist, namely as between those circuit-breakers which may have to deal with both symmetrical and asymmetrical conditions and those which may have only to deal with the symmetrical condition. The latter are generally assumed to be those circuit-breakers intended for use in those parts of a system generally remote from the power source where marked asymmetry cannot occur and where the short-circuit operating duty requirements and restriking voltage conditions are not severe. Such breakers are covered by B.S. 936 and Class A in A.S.T.A. No. 16.

The specified tests for breaking and making capacity in the two groups are therefore—

B.S. 116 and A.S.T.A. No. 16 Classes B and C.

(1) B–3′–B–3′–B at 10 per cent of rated symmetrical breaking capacity.

(2) B–3′–B–3′–B at 30 per cent of rated symmetrical breaking capacity.

(3) B–3′–B–3′–B at 60 per cent of rated symmetrical breaking capacity.

(4) B–3′–MB–3′–MB at not less than 100 per cent of rated symmetrical breaking capacity and not less than 100 per cent of rated making capacity.

(5) B–3′–B–3′–B at not less than 100 per cent of rated asymmetrical breaking capacity and with a d.c. component at the moment of contact separation not less than 50 per cent of the a.c. component in one phase in each breaking operation.

B.S. 936

(1) B–3′-MB at 30 per cent of rated symmetrical breaking capacity and making capacity.

(2) B–3′-MB at not less than 100 per cent of rated symmetrical breaking capacity and not less than 100 per cent of rated making capacity.

A.S.T.A. No. 16 Class A

(1) B–3′–B at 10 per cent of rated symmetrical breaking capacity.

(2) B–3′–B at 30 per cent of rated symmetrical breaking capacity.

(3) B–3′–B at 60 per cent of rated symmetrical breaking capacity.

(4) B-3′-MB at not less than 100 per cent of rated symmetrical breaking capacity and not less than 100 per cent of rated making capacity.

In the foregoing the symbols used have the following significance

B .. denotes a breaking operation.

M .. denotes a making operation.

MB .. denotes a making operation followed by a breaking operation without the introduction of any intentional time lag.

3′ .. The time in minutes between successive operations of an operating duty.

In addition to the foregoing tests, it is recognised that in certain circuit-breakers there may be a critical current, below the 10 per cent value, at which the arc duration is a maximum and shows a marked increase compared with that corresponding to the rated breaking capacity. To cover such contingency it is usual to submit circuit-breakers to an additional test at 5 per cent of the rated breaking capacity or less. The circuit-breaker illustrated in Chapter VI, Fig. 6-2, has in fact been tested down to 2·5 per cent as will be shown in the typical test data to be given later. In other tests, these circuit-breakers have been proved down to 1 per cent of rating.

As a further check on oil circuit-breakers which have all three poles within one enclosure, it is a requirement that the circuit-breaker is capable of breaking 100 per cent of the symmetrical breaking current applied to one pole, usually an outer pole. This test at phase-to-neutral voltage comprises one or more "break" shots to show that the operation is not adversely affected by unbalanced forces produced under such conditions. In service they might arise in the case of a fault between one line and earth where the impedance in the earth circuit is very low. Here again the circuit-breaker previously referred to has been subjected to such tests.

In all tests, the conditions must approximate closely to those expected in service and, for this reason, the recovery voltage and power factor must be within prescribed limits. Recovery voltage, or the voltage appearing across the open contacts at current zero, must not be less than 95 per cent of the rated service voltage for circuit-breakers up to and including 500 MVA. For larger breakers it is specified that the recovery voltage shall be as near to 100 per cent as possible, but a variation is permitted depending on the rating of the breaker and the test duty. This variation is permitted because it is not possible, due to limited size of test plants, to obtain high percentage values of recovery voltage at the higher values of test MVA, i.e. above 1 500 MVA, three phase. Extensions to British testing stations have made it possible to provide a recovery voltage not less than 67 per cent of the rated voltage.

Recovery voltage depends in some degree on the excitation of the test machine and on the power factor, the effect of the latter having been demonstrated in Chapter II, Fig. 2-1 and the various specifications include values of power factor for the test circuit, these not to exceed 0·15 for B.S 116 circuit-breakers up to 500 MVA and class B and C circuit-breakers to A.S.T.A. No. 16 and 0·3 for all others. In many short-circuit tests, values of power factor much below the specified values are obtained. In service, low power factors are to be expected at points close to a source of power and higher power factors at remote points.

In the tabulation of tests noted earlier, it is indicated that in the first group, Test No. 5 is one intended to prove the behaviour of a circuit-breaker when called upon to interrupt a highly asymmetrical current. As is well known, asymmetry occurs to a greater or lesser degree in all phases of a short-circuited three phase system and in one phase it will be much more pronounced than in the other two, so much so that this one phase might well be completely asymmetrical in the first major half cycle of short circuit as shown in Fig. 5-9. Where the degree of asymmetry in two phases is equal, then the third phase may be symmetrical.

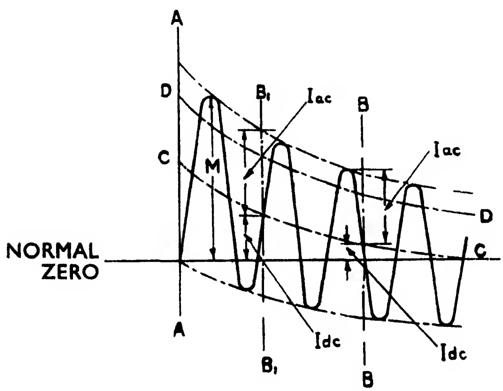
This illustration shows how the high degree of asymmetry at the commencement of a short-circuit is progressively reduced until at some point the curve of short-circuit current will become symmetrical, i.e. reach its steady state. In the majority of circuit-breakers contact separation will occur before this steady state is reached so that they will always be called upon to deal with some degree of asymmetry. For this reason, standard specifications state that in all symmetrical breaking capacity tests, the d.c. component (see Fig. 5-9) shall *not exceed* 20 per cent* of the a.c. component, but in the asymmetrical test, the d.c. component must *not be less* than 50 per cent of the a.c. component, the value 20 per cent relating to *any* phase and the value 50 per cent to *one* phase. Thus, from Fig. 5-9 it is seen that the point of contact separation is important in the various tests to ensure compliance with the specified limits of d.c. component, and in the asymmetrical test it may be necessary, to ensure the 50 per cent d.c. component at contact separation, to energise the circuit-breaker trip coil slightly in

**In many tests much lower values are obtained and, theoretically, the d.c. component could be zero. For circuit-breakers above 500 MVA, test authorities may allow a d.c. component in excess of 20 per cent in tests 3 and 4 provided the value of active recovery voltage is reduced—see Clause 51 (e) B.S. 116 : 1952.*

advance of the closing of the making-switch to apply the short-circuit, so that the contacts have begun to move and they will separate at a very early point in the current wave e.g. at B_1B_1 in Fig. 5-9. Otherwise, if the breaker is tripped after the short-circuit starts, its normal operating time to the point of contact separation may produce a value of d.c. component well below 50 per cent, e.g. at BB in Fig. 5-9.

It may be noted here that different circuit-breakers are affected in different ways by asymmetry in the current wave and, broadly, these differing performances are dependent on whether or not the design is sensitive to voltage and not so much to arc energy or vice versa. These are, very roughly, the differences between air-blast and arc-controlled oil breakers.

All circuit-breakers must be tested for ability to "make" on to a short-circuit and here the asymmetrical condition is unavoidable. The current at



AA = START OF SHORT-CIRCUIT

BB & B_1B_1 = INSTANTS OF CONTACT SEPARATION

Iac = PEAK VALUE OF AC COMPONENT OF CURRENT AT CONTACT SEPARATION

Idc = DC COMPONENT OF CURRENT AT CONTACT SEPARATION

$\frac{\text{Idc}.100}{\text{Iac}}$ = PERCENTAGE DC COMPONENT AT CONTACT SEPARATION

CC = DISPLACED ZERO-LINE OF CURRENT WAVE

DD = RMS VALUE OF SYMMETRICAL CURRENT AT ANY INSTANT MEASURED FROM CC

$\frac{\text{Iac}}{\sqrt{2}}$ = RMS SYMMETRICAL BREAKING CURRENT

$\sqrt{\left(\frac{\text{Iac}}{\sqrt{2}}\right)^2 + \text{Idc}^2}$ = RMS ASYMMETRICAL BREAKING CURRENT

M = MAKING CURRENT (PEAK VALUE)

FIG. 5-9.—*Illustrating symmetrical and asymmetrical values of short-circuit current and peak making current.*

contact touch will be the peak current in the first half-cycle (major loop) of short-circuit and if, as we have discussed earlier, complete asymmetry occurs in one phase, this peak value can reach the very high figure of 2·55 times the r.m.s. value of symmetrical current for power factors of 0·15 or less and 2·0 times for power factors of about 0·3. This peak value M is shown in Fig. 5-9 and thus if the r.m.s. value of symmetrical current broken on a particular circuit is shown to be, say, 21 900 amperes, the circuit-breaker can be called upon, under the worst circumstances, to "make" on to a peak value of 56 000 amperes.

The severity of duty imposed on a circuit-breaker closing on to a short-circuit is largely due to the magnitude of the electromagnetic effects caused by the high peak current, which we shall note in Chapter VI when discussing contact grip and loop effects.

It will be noted that when testing for "make" operations a "break" operation immediately follows, because it may be assumed that with a fault on the system it should be immediately cleared, hence the test covers "MB" duty. It is of interest here to note that standard specifications recognise the existence of two classes of circuit-breaker, one described as having a "fixed trip" such that the breaker is free to trip only when it is fully closed, and the other described as "trip-free" and such that it is free to open immediately the tripping impulse is applied during a closing operation.

Thus, when carrying out short-circuit tests, a circuit-breaker of the fixed-trip type must, when making on to the short-circuit, latch in the fully closed position before re-opening to perform the break part of the test. In the trip-free type, the tripping impulse may be given at any time during the closing stroke and thus the time interval between contact-make and contact-break may be very short, with the result that at contact-break the d.c. component may be considerably greater than the symmetrical break condition requires, i.e. not more than 20 per cent of the a.c. component. In such circumstances the test authority is permitted to segregate the make-break tests and carry out separate break and separate make tests. When separate tests are made, it is necessary to demonstrate, or test evidence must be produced, that the apparatus under test is capable of performing a make-break test duty (MB–3–MB) at values of voltage as near to the rated values as is practicable for the test plant. In this connection, too, Clause 52 of B.S. 116 details other requirements which have to be met, and certain permissible variations.

In certain classes of circuit-breaker the characteristics may be such as to inherently reduce the short-circuit current value below that which would appear had the circuit-breaker not been present. In such cases, the circuit-breaker will be credited with interrupting or making the values of current derived from what is termed prospective current tests, i.e. tests to produce oscillograms similar to that in Fig. 5-9 without the breaker present. This condition is particularly applicable to h.r.c. fuses.

Tests such as those described will all be recorded on oscillograms from which the test authority will measure the various values of current, voltage, pressure, arcing and total operating times etc., and it is of interest in this connection to consider two oscillograms, Figs. 5-10 and 5-11, which have been specially marked to show the points of measurement. The first oscillogram is that of a "break" test and the second that of a "make break"

test, but before these can be fully studied it is necessary that certain no-load timing tests be made from which it is possible to determine the exact point on the travel curves at which contact "break" and contact "make" occurs in the circuit-breaker under test, and also to show the relationship between these happenings and the impulse given to the trip coil on breaking or the closing coil on making. Oscillograms are therefore taken, on which will be recorded four traces to show, in the case of the breaker opening, the trip coil current, the opening travel curve of the moving contacts, the instant of contact separation and a 50 cycle (or other frequency) timing wave, all as shown typically in Fig. 5-12, or in the case of the breaker closing the contacts touch instead of separation, and closing coil current instead of the trip-coil and the travel curve of closing instead of opening.

To obtain the trace of contact separation, current (usually d.c.) is passed through the closed contacts of the circuit-breaker to an oscillograph element so that, initially (while current flows), the spot is deflected above zero and, when the contacts separate, the spot assumes its zero position.

The trace which indicates the travel of the contacts is obtained by d.c. current passing through a variable resistance, the slide of which is connected to the moving contact system, resistance being cut out as contact is made with each successive stud and thus giving a stepped curve. This curve

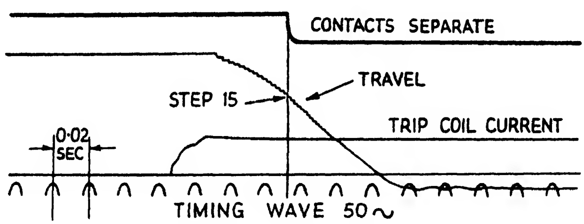


FIG. 5-12. *Typical timing oscillogram for breaker opening*

enables the speed of break to be determined and shows how, initially, the speed of movement is slow due to the friction between the fixed and moving contacts and how, after separation, considerable acceleration occurs. It is often necessary to cushion the moving contact system at the end of its stroke by means of oil or air dash-pots and this may be reflected in the travel curve by a suggestion of rebound prior to the contact system finally settling in the dash-pot.

From these two traces it will now be noted that it is possible to determine at which step on the travel curve contact separation occurs or, conversely, where contact make occurs, and enables the line of contact separation to be marked on the oscillogram of actual short-circuit test as will be seen later.

In making this timing test, the trip coil which causes the circuit-breaker to open is automatically energised by the oscillograph and a trace of the current in the coil is recorded.

The timing wave trace is simply the trace of a 50 cycle wave (only the upper half being recorded in the example shown) and gives a measure of time, this being 0·02 second between successive peaks.

How these timing oscillograms are used in the interruption of an oscillogram of actual short-circuit test can now be seen by reference to Figs. 5-10 and 5-11. At the foot will be seen the travel curve, the trip coil, closing coil, current curve and the timing wave discussed earlier.

Studying first the oscillogram of a "break" test, Fig. 5-10, it will be noted that three vertical lines are drawn marked "M", "CS" and "B", respectively.

The line "M" is drawn at the point at which short-circuit occurs (initiated by closing of the making switch), a point easily discernible as that at which current wave traces begin.

The line "CS" is drawn at the point of contact separation determined from the timing wave after reference to the timing oscillogram, i.e. in Fig. 5-12, the point of contact separation is noted as being at step 15, and by counting this number of steps on Fig. 5-10 the point "CS" is determined.

The line at "B" indicates the point at which final interruption of the short-circuit is made and is determined by reference to the traces of current where the last phase to clear becomes zero. From the information so far noted, coupled with reference to the 50 cycle timing wave and the trip coil current curve, it is possible to determine the following—

(a) The opening time of the circuit-breaker, measured horizontally from point "T" (trip coil energised) to point "CS".

(b) The arcing time, measured horizontally from point "CS" to point "B".

(c) The total break time, measured horizontally from point "T" to point "B".

(d) The arc length, measured vertically between points "CS" and "B" as indicated.

The record of Fig. 5-11 is not very different from Fig. 5-10 but here the short-circuit is made by closing the circuit-breaker under test to complete the short-circuit and the breaker "makes" and then "breaks". Hence, the travel curve in this illustration shows the movement of the contact bar in two directions.

Three lines are drawn as in the earlier description, that at "CM" being the point at which the contacts touch on the closing stroke, i.e. at step 15. Other points ("CS" and "B") are determined as previously, while the distance measured horizontally between "CM" and "B" is the total make-break time of the circuit-breaker. This illustration has one additional trace, i.e. that of closing coil current.

We may now consider in some detail the other records which these oscillograms show.

Right at the top is a trace "V_L" giving the line to line voltage. Initially, this records the open-circuit voltage at the generator terminals. Close examination of this trace will show that at the point "M" (or "CM") there is a reduction in the voltage. The value of this reduction is equal to the inductive drop in the generator windings, and it is a progressive reduction as the generator field is demagnetised.

At the point "B", the short-circuit is cleared and the generator terminal voltage builds up slowly to its original open-circuit value.

Three current traces are now noted, for the red, yellow and blue phases respectively. Up to the point of short-circuit ("M" or "CM"), this trace is a zero reading. Thereafter, it follows a sine-wave form until clearance is made at "B".

It should be particularly noted that these traces are, with one exception (i.e. that for the blue phase current in Fig. 5-11), all offset to some degree about zero, thus illustrating the asymmetry of which note has been made earlier.

The current broken is measured at the instant of contact separation "CS", and it will be recalled that in certain duty cycles, symmetrical values of current are used, whilst in one duty cycle it is the asymmetrical value of current which is used. The current in the first case is not considered to be symmetrical if the d.c. component in any phase exceeds 20 per cent. In the second case, to be asymmetrical, the current in one of the phases must have a d.c. component of 50 per cent or more.

In Figs. 5-10 and 5-11 the d.c. component is shown by Id and the peak a.c. component by Ia and it follows that the—

$$\text{a.c. component} = \text{Ia} = \frac{\text{OP}+\text{ON}}{2}$$

$$\text{d.c. component} = \text{Id} = \frac{\text{OP}-\text{ON}}{2}.$$

$$\%\ \text{d.c. component} = \frac{\text{Id}}{\text{Ia}} \cdot 100$$

For symmetrical breaking current, the r.m.s. symmetrical value is

$$\frac{\text{Ia}}{\sqrt{2}}$$

For asymmetrical breaking current, the r.m.s. asymmetrical value is

$$\sqrt{\left(\frac{\text{Ia}}{\sqrt{2}}\right)^2 + \text{Id}^2}$$

In a "make-break" shot, the breaker contacts have to close on to a peak current as we have previously noted. The value of this peak current is that of the first *major* loop of the current wave after the instant of short-circuit "CM" (Fig. 5-11) and is marked Im, measured between the current zero line and the peak of the wave. It is of interest to note that the current wave of red phase current shows a *minor* loop immediately after "CM" and this is ignored, the making current in that phase being that of the major loop which immediately follows.

We can now consider the three traces which record the phase voltages, red, yellow and blue. It is best to consider first the record of these voltages for the make-break test, Fig. 5-11.

Initially, the full phase-volts are across the open circuit-breaker contacts. At the point "CM" where current starts due to closing of the contacts, the voltage falls to zero, being absorbed in the generator windings and the series reactors. At the point "CS" where the contacts separate an arc is struck which continues until final extinction at point "B". Between these two

points it is noted that voltage appears, first above, and then below the zero line in succession as the current alternates above and below zero. This voltage is the arc voltage (see also Chapter II) and, since the arc path is almost pure resistance of a value proportional to the arc length for a given current, the arc voltage is in phase with the current and its value progressively increases as the arc lengthens due to the contacts separating.

Close examination of the oscillograms will show that the arc is extinguished in one phase before the other two. This is because the current in an a.c. circuit can be extinguished only at a normal zero or very near to it. Since current zero occurs at different instants in the three phases, one phase must be interrupted first. When this occurs, the currents in the other two phases are equal and opposite and the circuit becomes single phase. Both of these currents will be interrupted at the subsequent zero since one phase acts as a return path for the other.

At the instant when the arc is extinguished in the first phase, the voltage across the arc path rises to a value which may reach 1·5 times the open circuit value (refer Chapter II, Fig. 2-4).

Furthermore, it is at point B that transient voltages appear (as described earlier) and these can be studied only by means of a cathode-ray oscillogram. Subsequently, the voltage assumes a normal sine-wave form and this is known as the recovery voltage (not to be mistaken for or confused with the transient restriking voltage). This recovery voltage must reach a prescribed value as set down in B.S. 116 or B.S. 936 and it is measured between lines during the second complete half-cycle after final interruption (point "B").

This is shown at RR_1 in Fig. 5-11 and if Vr is the recovery voltage line/line) then,

$$Vr = \frac{RR_1}{2\sqrt{2}}$$

Alternatively, the line to line recovery voltage may be derived from the average value of the phase components (Vph) measured in each phase during the second complete half-cycle after "B" thus—

$$Vr = \sqrt{3}\,Vph \text{ for a three phase test}$$

$$\text{where } Vph = \frac{1}{3}\left(\frac{Va}{2\sqrt{2}} + \frac{Vb}{2\sqrt{2}} + \frac{Vc}{2\sqrt{2}}\right)$$

and where Va, Vb and Vc are the red, yellow and blue phase voltages respectively, indicated in Fig. 5-11 as $2\sqrt{2}$ Vrc in each voltage trace.

The phase voltage traces in a "break" test, Fig. 5-10, differ from those in a "make-break" test in that no voltage is recorded prior to the commencement of current flow because the circuit-breaker under test is isolated from the power source by the open condition of the making-switch.

Examination of the traces of phase voltage between the points "M" and "CS" or "CM" and "CS" show that they undulate slightly. In some heavy current tests this is much more pronounced and is due to the resistive and inductive drops across the circuit-breaker and its connections prior to contact separation.

Three further traces on the oscillograms represent the power absorbed in the arc in each phase. These are noted as red, yellow and blue phase kW

respectively and the deflection at any point is proportional to the instantaneous values of arc-current and voltage across the arc. Note that the deflection is always in the same direction, i.e. above the zero line, because the arc power factor is unity. By determining the area of the trace above the zero line, the energy consumed can be obtained with the aid of appropriate kilowatt and time scales. This value is stated in kW seconds.

For circuit-breakers which employ oil as the insulating medium it is usual to record the pressure attained within the tank and is shown in Figs. 5-10 and 5-11 recorded in lb. per sq. in. by measurement against a pressure scale. In oil circuit-breakers having arc-control devices, most of the pressure will be contained within the devices, showing only relatively low values in the tank. By special arrangements it is possible to record the pressure within the arc-control device.

There is one other important test for circuit-breakers, namely that to determine the ability to carry short-circuit current for a given period of time. This is necessary because under fault conditions the short-circuit current may have to be carried by two or more circuit-breakers in series, the one nearest the fault having the duty of interrupting the fault (by reason of discriminating protective gear), those further back in the line having to carry the current but not trip out.

That a circuit-breaker will perform this latter task is proved by the short-time current test, the time period being determined as 3 seconds where the ratio of the rated symmetrical breaking current to the normal current is equal to or less than 40 or 1 second where the ratio as above is more than 40, noting that for circuit-breakers to B.S. 936 only a 1 second rating is specified. In all cases except those where the breaker is fitted with series-trip coils or overcurrent release coils, the rated 3-second or 1-second short-time current must not be less than the rated symmetrical breaking current. Appendices to the appropriate British Standards give details as to the procedure of measurement and calculation of the equivalent r.m s. value of current over the period of test.

At this stage it will be of interest to study the data which accompanies any series of proving tests and for this purpose it is convenient to take that which applied to the series of tests which resulted in the certificate shown in Fig. 5-2 for an oil circuit-breaker with arc-control devices and assigned the following ratings to B.S. 116:1952, Class A.

Service voltage	11 kV
Normal current	800 amperes
Breaking capacity at 11 kV	
Symmetrical	18·4 kA (equivalent to 350 MVA)
Asymmetrical	23·0 kA
Making capacity	46·8 peak kA at kV
Operating duty	B–3′–MB–3′–MB

The data applicable to the tests are given in Table 5 : 4, it being noted that all were made at power factors less than 0·1 lagging

To illustrate these tabulated results, two of the oscillograms are given in Figs. 5-13 and 5-14, being respectively those for second make-break test in Test duty No. 4 and one of the additional tests made on one pole of the breaker.

TABLE 5 4

Test duty No B S 116	Test and oscillogram No	Operation and time interval in minutes	Breaking Current Symmetrical Phase kA	Breaking Current Symmetrical Average kA	Breaking Current Asymmetrical kA	D C component	Making current peak kA	Recovery voltage between phases kV	Arc duration loops (half cycles)	Total break time 1 100th sec	Make break time 1 100th sec
1	590601 31	B	1 87 1 89 1 91	1 89	—	—	—	11 6 (106%)	6 3 6 0 4 7	11 8	—
		3									
	590601 32	B	1 87 1 89 1 90	1 89			—	11 6 (106°)	6 7 6 3 7 0	11 4	
		3									
	590601 33	B	1 87 1 89 1 90	1 89	—	—		11 6 (106)	4 4 6 0 5 7	11 4	—
2	590601 28	B	5 72 5 85 5 75	5 77		—	—	11 1 (101%)	2 9 3 7 3 3	9 0	—
		3									
	590601 29	B	5 72 5 85 5 75	5 77	—	—	—	11 2 (102%)	5 0 4 7 3 3	10 4	—
		3									
	590601 30	B	5 70 5 88 5 80	5 79	—	—	—	11 2 (102%)	4 5 4 2 4 8	10 1	—

TABLE 5 : 4—*continued*

Test duty No B.S. 116	Test and oscillogram No.	Operation and time interval in minutes	Breaking Current			D.C. component	Making current peak	Recovery voltage between phases kV	Arc duration loops (half-cycles)	Total break time 1/100th sec	Make-break time 1/100th sec.
			Symmetrical		Assymmetrical						
			Phase kA	Average kA	kA	%	kA				
3	590601–25	B	11.2 11·4 11·5	11·4	—	—	—	11·2 (102%)	1·4 3·1 2·8	8·4	—
		3									
	590601–26	B	11·0 11·1 11·4	11·2	—	—	—	11·0 (100%)	1·5 2·2 1·8	7·5	—
		3									
	590601–27	B	11·2 11·2 11·4	11 3	—	—	—	11·2 (102%)	2·5 3·2 2·9	8·5	—
4	590602–08	B	18 3 18·5 18·5	18·4	—	—	—	11·0 (100%)	2·0 2·6 2·3	9·5	—
		3									
	590602–09	MB	18·3 18·5 18·4	18·4	—	—	40·5 53·0 42·2	11·1 (101%)	1·1 1·7 1·5	7·8	16·9
		3									
	*590602–10	MB	18·2 18·5 18·5	18·4	—	—	31·3 52·0 48·5	11·1 (101%)	1·5 2·1 1·8	8·0	17·0

TABLE 5 : 4—*continued*

Test Duty No. B.S. 116	Test and oscillogram No.	Operation and time interval in minutes	Breaking Current			D.C. component	Making current peak	Recovery voltage between phases	Arc duration loops (half-cycles)	Total break time 1/100th sec.	Make-break time 1/100th sec.
			Symmetrical		Assymmetrical						
			Phase kA	Average kA	kA	%	kA	kV			
5	590601–05	B	18·9 18·9 18·9	18·9	22·0 20·6 20·1	42 32 10	—	11·1 (101%)	0·6 1·3 1·0	7·6	—
		3									
	590601–06	B	18·9 19·0 19·0	19·0	25·6 22·8 19·4	65 47 15	—	11·0 (100%)	0·8 1·6 1·2	6·6	—
		3									
	590601–07	B	19·2 19·3 19·3	19·3	25·2 28·6 19·7	61 75 15	—	11·1 (101%)	1·6 1·0 1·9	7·0	—
Extra test duty at 2½% of rating	590602–14	B	0·450 0·460 0·450	0·453	—	—	—	11·0 (100%)	5·6 5·3 2·9	11·6	—
		3									
	590602–15	B	0·450 0·470 0·460	0·460	—	—	—	11·0 (100%)	6·6 6·3 5·9	12·6	—
		3									
	590602–16	B	0·450 0·470 0·460	0·460	—	—	—	11·0 (100%)	6·5 6·2 6·8	12·8	—
Single pole tests clause 52(g) B.S. 116	590605–28	B	18·4	—	—	—	—	11·0(100%)	1·6	6·2	—
		3									
	*590605–29	B	18·7	—	—	—	—	11·1(101%)	2·7	7·7	—
		3									
	590605–30	B	18·8	—	—	—	—	11·0(100%)	1·9	6·2	—

**These oscillograms reproduced as Figs.* 5-13 *and* 5-14.

All data in the above table have been produced by permission of N.V. tot Keuring van Electrotechnische Materialen (KEMA) from their Report No. 4782-59 *covering tests on a circuit-breaker for Messrs. Johnson & Phillips Ltd., rated* 350 *MVA at* 11 *kV.*

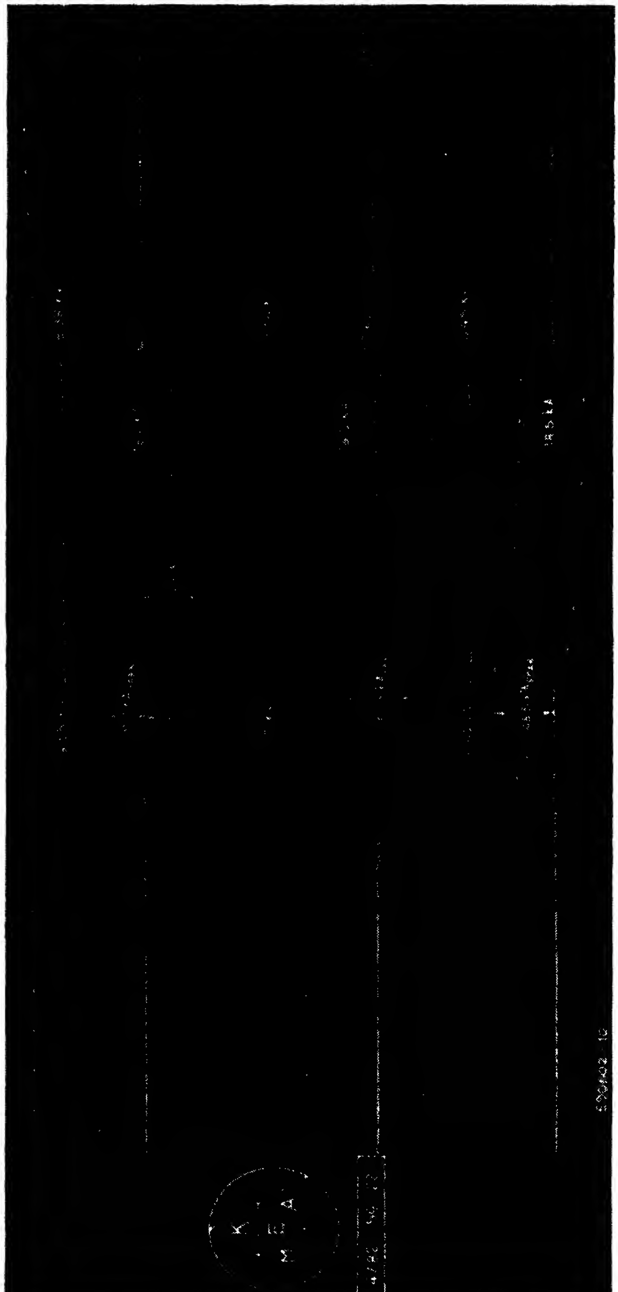


FIG. 5-13.—*Oscillographic record of oil circuit-breaker performance, test duty No. 4—Table 5 : 4 second make-break test (Johnson & Phillips Ltd.).*

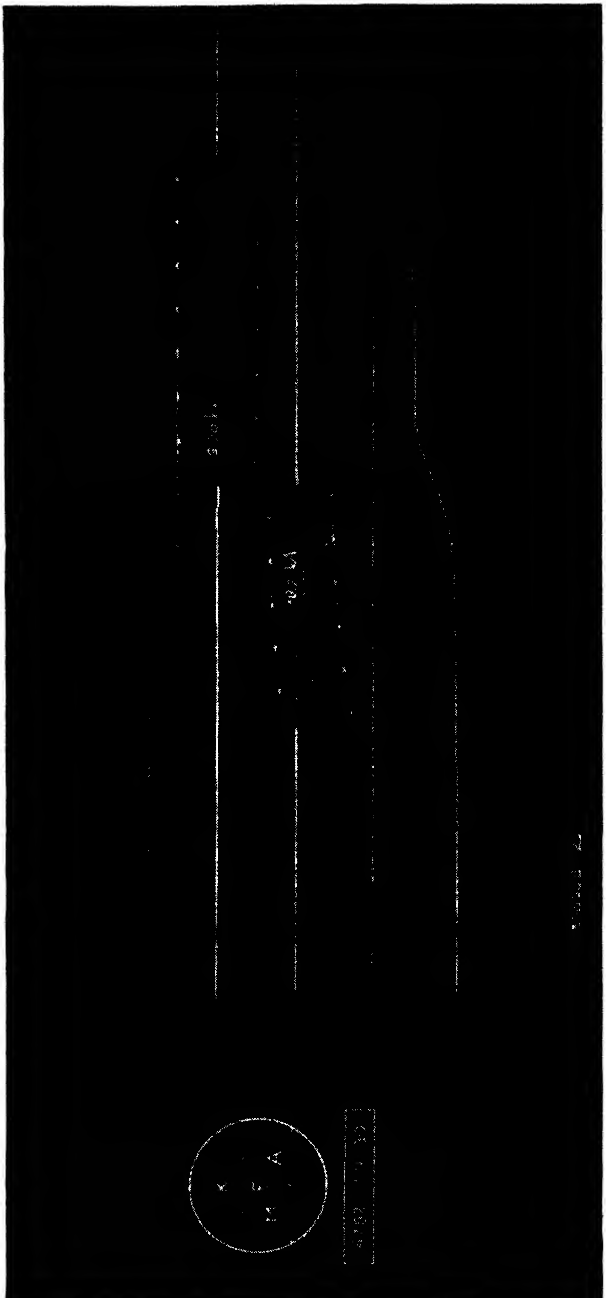


FIG. 5-14.—*Oscillographic record of oil circuit-breaker performance, single pole test at full rated interrupting current—see Table 5 : 4 (Johnson & Phillips Ltd.).*

The rules for short-circuit testing of circuit-breakers include a variety of departures and alternatives acceptable under certain prescribed conditions in addition to data as to what is and what is not permitted in the course of testing. The extent of this material is such as to preclude reference here and the reader must therefore be referred to the British Standards or A.S.T.A. rules for details.

In Chapter VI note will be taken of the more extensive use being made today of oil switches on distribution systems at 3·3 to 33 kV. These switches are primarily intended for isolating and earthing ring main circuits by hand without protective devices and therefore are not called upon to break short-circuit current. They are, however, subject to (a) being closed on to a fault and therefore must have a rated making-capacity and (b) carrying a through fault for a period of time, e.g. 3 seconds, and must have a short-time rating. The requirements for the testing of this apparatus have been included in B.S. 2631 : 1955 and show that the following should be complied with.

1. The main switch must be capable of breaking normal load and charging currents and test duty cycles B–3–B–3′-B at 130 per cent and 30 per cent of normal current rating, e.g. 400 amperes, are specified at a power factor of 0·7 lag.
2. The main switch *and the earthing switch* must both be capable of making on to the peak current in the first half cycle of short-circuit (as previously described) and a test duty cycle M–3′–M at 100 per cent of making capacity is specified and on "making", must be held for at least 10 half-cycles.

B.S. 2631 schedules a range of standard sizes which indicates that at each voltage a preferred upper limit of making capacity is 33·4 kA peak and a through short-time rating of 13·1 kA for 3 seconds.

There are in use today a number of circuit-breakers and automatic switches which, in themselves, have only a limited breaking- and making-capacity but when backed up by h.r.c. fuses or fuse-links can be regarded as being adequate for use on systems whose fault values are within the rating of the fuses or fuse-links. Tests to prove such combinations have been enumerated in A.S.T.A. No. 22 and include tests under circumstances where the fuse-link has or has not been separately tested, tests to prove the ability of the circuit-breaker or switch to make and break fault current within its own ability, i.e. fuse links replaced by links, and tests at five times the normal current rating or twice the take-over current (i.e. the current at which the fuse-links take over the current-breaking duty from the circuit-breaker or switch) whichever value is the higher, again with the fuse-links replaced by links.

Tests made with the fuses or fuse-links present must be at power factors applicable to the type of fuse-link and the British Standard appropriate to the type, e.g. B.S. 88. Tests made with the fuse-links removed may be at a power factor not exceeding 0·7 lagging.

Particularly for h.v. rural distribution, the use of fuses, usually pole-mounting, is an economical form of protection and in B.S. 2692 : 1956 a range of such fuses is covered for voltages in the range 2·2 to 66 kV and with breaking capacities from 25 to 750 MVA three phase. This specification

has to recognise the existence of various types of fuse such as liquid, oil-tank, current limiting, etc., and in addition, those used in the primary circuit of a voltage transformer and a comprehensive series of short-circuit tests are given to cover these various types.

Some idea of the short-circuit powers available for testing have been noted earlier and it will be clear that these powers cannot, except at very high cost, keep pace with the ever-increasing short-circuit MVA associated with modern high-voltage high-power systems, e.g. 35 000 MVA or more. Thus, circuit-breakers designed to meet these high MVA values cannot be submitted to full scale testing, but as will be seen in Chapter VIII many of these circuit-breakers are of the air-blast type employing several identical interrupting heads in series per phase and it is therefore possible to assess the behaviour of a complete circuit-breaker up to its rated making and breaking capacity from tests made on one or more of the interrupting heads, at an appropriate fraction of the full recovery voltage. This method of testing requires that the design of the breaker as a complete unit is such as to ensure equal voltage distribution between all the breaks in series, a feature normally achieved by shunting each break with resistance or capacitance, as noted later in our discussion on air-blast circuit-breakers. To cover this form of unit testing, a set of rules has been issued by A.S.T.A. in their document No. 15.

BIBLIOGRAPHY

British Standard Specifications Nos. 88, 116, 936, 2631 and 2692.

Switchgear Principles, P. H. G. Crane (Cleaver Hume Press Ltd.).

"Proving the Performance of Circuit-Breakers with particular reference to those of large capacity", J. Christie, H. Leyburn and J. Bird. Proceedings I.E.E. Paper No. 1707S, Dec. 1954 (102 Part A, page 697).

"A New Testing Station for High Power Circuit-Breakers", J. Christie, H. Leyburn and J. Bird. Proceedings I.E.E. Paper No. 1736S, Dec. 1954 (102 Part A, page 709).

"Application of High-Speed Ciné Photography to Switchgear Research and Design", J. A. Thomas, F. A. Roberts and D. Legg. The B.E.A.M.A. Journal, Feb. 1958.

CHAPTER VI

OIL CIRCUIT-BREAKERS AND OIL SWITCHES

CHAPTER VI

OIL CIRCUIT-BREAKERS AND OIL SWITCHES

(In spite of the extensive development of air-break and air-blast circuit-breakers in their respective voltage ranges, the oil circuit-breaker is still the most widely used type of interrupting device for power networks up to 66 kV and is still favoured in many quarters for voltages up to the highest in use today.) That this should be so can be attributed to the fact that technical achievement in British designs has far exceeded that of other countries and that on economic grounds the oil circuit-breaker more than holds its own with alternative devices.

The technique of oil circuit-breaker design would be relatively simple if the device had nothing more onerous to do than to make and break the normal power current in an electrical circuit. In other chapters, however, we have seen that when a short-circuit occurs on a system, the fault current can reach very high values and the circuit-breaker has the more difficult task of interrupting this current under very different conditions of severity In other circumstances it may need to be closed on to an existing fault, a task often more onerous than that of breaking fault current. In addition, the breaker may be called upon to carry a through fault i.e. to carry the fault current without opening for a period of time while the short-circuit is being cleared elsewhere.

Before considering in detail the established features which go to make up the modern oil circuit-breaker, it is interesting to compare a typical example in the voltage range up to 11 kV, with a design in the same range used about 30 or 40 years ago. A breaker of such early type is shown in Fig. 6-1, the design being of the simplest form, comprising sets of moving contacts of a particularly flimsy nature which make contact with fixed buttons at the lower end of the porcelain insulators. The latter, as can be seen, had corrugated surfaces on the outer ends, the purpose of which was (mistakenly) to give increased electrical clearance to earth. The oil tank is a simple structure of thin sheet metal and is fixed to the top plate by means of four hinged studs with wing-nuts.

Compare this with the breaker shown in Fig. 6-2. Here the moving contact system comprises three robust solid round copper rods which make and break contact with suitable fixed finger contacts on the through insulators, the operation of making and breaking taking place within an arc control device. The corrugations have disappeared from the insulators, and the oil tank is constructed of heavy boiler plate, suitably reinforced, and held to the top plate by high tensile steel studs of relatively large diameter. Note, too, the change in top plate construction. In Fig. 6-1 the plate (probably of cast-iron) is flat and the contact lifting rod projects through it to atmosphere and is coupled to the operating handle by means of a single lever. In Fig. 6-2 the top plate is a box structure of heavy boiler plate, the whole of the operating mechanism being contained within the box. Another point of difference between the two designs is that no particular provision was made

to relieve the internal pressures set up due to fault clearance in the design shown in Fig. 6-1, but in the design illustrated in Fig. 6-2, adequate venting is provided which, while giving relief to internal pressure, minimises the loss of oil through the vent.

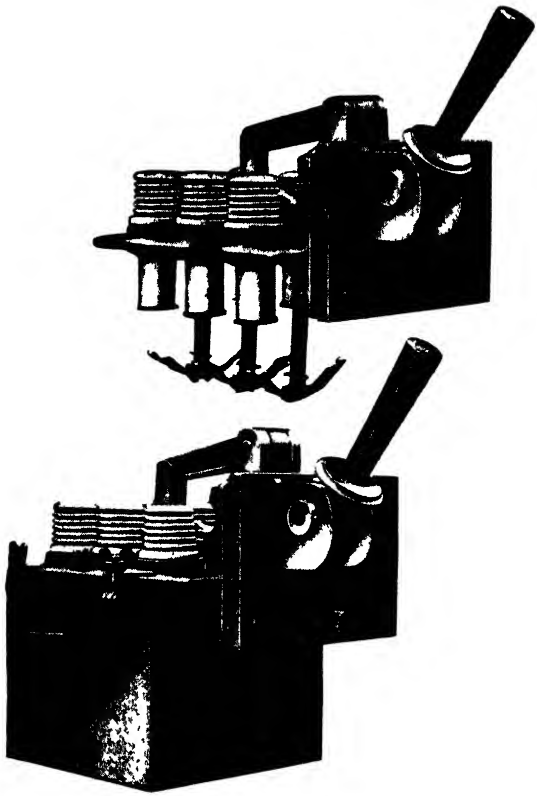


FIG. 6-1.—*A early type of circuit-breaker.*

The design of most early oil circuit-breakers was based largely on certain empirical formulae, operating experience and a number of basic factors regarded as being of importance and on a comparison of which competitive offers were judged by the user. These factors included:—

Volume of oil
Speed of break
Length of break
Head of oil above contact break
Volume of air cushion above oil
Electrical clearances

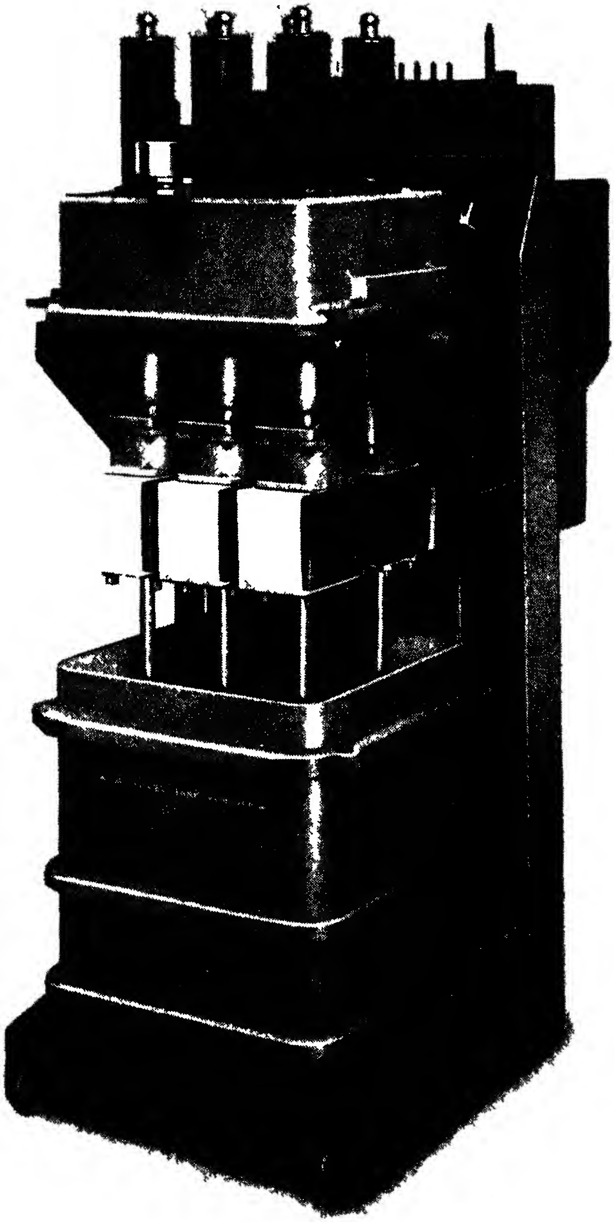


FIG 6-2 —*A modern oil circuit breaker with arc-control devices (Johnson & Phillips Ltd)*

With the coming of high-power short-circuit test plants came the realisation that not one of these factors alone or in combination was necessarily decisive and certainly mere magnitude was not proof of interrupting ability.

It has been shown, for example, that circuit-breakers having an exceedingly small oil volume can match the interrupting ability of those containing much greater quantity. Similarly, while it is obviously desirable that the moving contacts, opening to clear a fault, should reach the point at which the arc is interrupted as quickly as possible, it is known that high speed operation can result in long arcs because of the greater distance the moving contacts travel between current zeros and at which interruption occurs On the other hand, if the speed of break is too low at contact separation, there is the possibility that welding of the fixed and moving contacts may occur, a disastrous consequence on short-circuit clearance.

This problem of speed of break is one which is affected by a number of factors, some concerned with the design (e.g. double or single-break and, if the latter, whether the break is horizontal or vertical) and others inherent in a.c. systems as for example contact "grip" and the electromagnetic forces set up in the loop formed by the terminal stems and the moving contact bar. In addition, where the "break" is vertical, gravity assists in opening the breaker once the contacts have parted.

The energy for initiating the opening movement once the latching-in mechanism has been upset is derived from accelerating springs which have

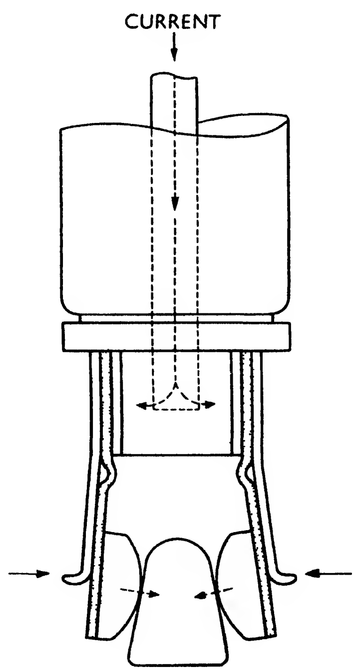


FIG. 6-3.—*Contact "grip".*

been compressed by the closing of the circuit-breaker. These springs are opposed in the first movement not only by the frictional resistance of the engaging contacts but by contact "grip". This is shown typically in Fig. 6-3 noting that when current flows from the fixed contacts to the moving contact, electromagnetic fields are set up which tend to force the fixed contacts on to the moving contact as shown by the arrows. These forces can be quite considerable when the current reaches short-circuit magnitude.

On the other hand, the accelerating springs get some help in their task in double-break designs by loop forces which are shown in Fig. 6-4, and thus offset the opposition due to "grip"

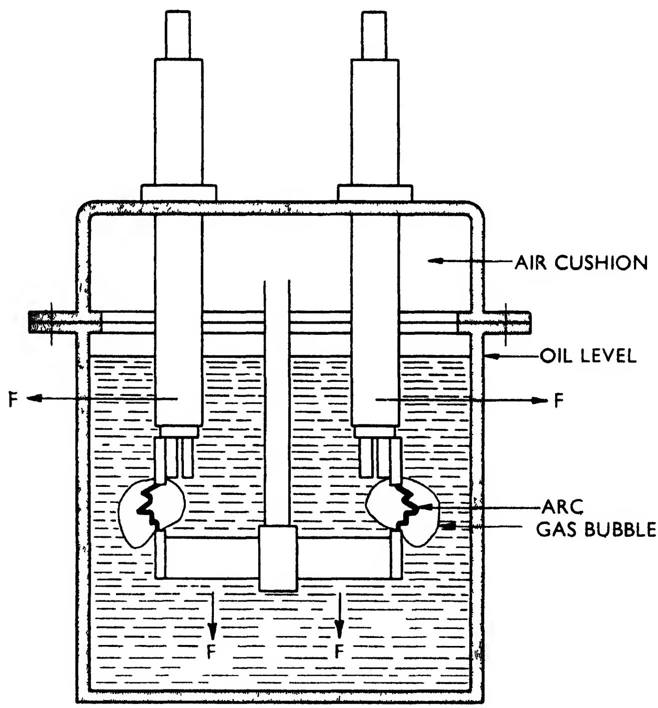


FIG. 6-4 —*Schematic diagram to illustrate oil circuit-breaker and electro-magnetic loop forces in direction of arrows F*

Another factor in speed of break is that there must be some resistance from the oil to the moving contact system, and this becomes particularly important where the circuit-breaker may be used in cold climates resulting in the oil becoming very viscous.

High speed of break can lead to other problems, not least among them being that of arresting the motion at the end of the stroke. Many designs accomplish this by a dashpot which is filled with oil from the breaker tank, and by this means bouncing at the end of the stroke is prevented.

This form of buffering has the disadvantage that when the breaker is taken out of the tank for maintenance, the dashpot may be empty and the breaker may be opened on check operations without means of arresting the moving parts. In very small circuit-breakers, the desired result can be achieved by simple springs.

Having fitted powerful accelerating springs to get the moving contacts away it now has to be remembered that the circuit-breaker has to be closed against them. The possibility of having to close on to a short-circuit cannot be ignored and here the electromagnetic forces set up at contact touch (or just before) are tending to oppose the closure just at the time when the accelerating springs are reaching the point of maximum compression, so that the closing mechanism has to be powerful and, for the high values of fault current, the operation must be taken out of the hands of the operator e.g. by solenoid or spring-closing mechanisms.

The speed of opening can also be seriously retarded by the pressure set up inside the oil tank, this pressure acting on the moving crossbar carrying the contacts. Cases are on record where reclosure has occurred owing to the difference of pressure between the inside and outside of the tank, this being most likely to occur in designs (if they still exist) where the contact lift rod passes through the top plate to atmosphere (as shown in Fig. 6-1) The majority of modern oil circuit-breakers, however, have the whole of the operating mechanism, except the final link to the handle gear, within the breaker dome or top plate, thus equalising the pressure on all moving parts

The distance between the co-operating contacts in the fully open position is known as the length of break and is a function of voltage; it must therefore be of such dimension as to have an adequate margin over the length of arc which may be drawn. A short length of break in which the arc might be maintained across fully opened contacts may result in destruction of the circuit-breaker.

The head of oil above the contacts affects gas bubble formation and must be sufficient to ensure ample pressure at the arc and to prevent the occurrence of a chimney of gas from the arc to the oil surface. A small volume of air above oil level means a higher pressure for a given volume of gas, a condition, however, which results in a desirable reduction of arcing time The correct values are determined by test and it is important in service that the manufacturers' indicated oil level and, in consequence, the air cushion, is maintained. It is interesting to note that in certain proving tests, circuit-breaker performance has been improved by the apparently simple expedient of increasing the head of oil by a fraction of an inch and thereby reducing the air cushion by a similar amount.

Both tank and top plate must be capable of withstanding the internal gas pressures generated. The general tendency is for the oil above the contacts to be thrown, *en masse*, upwards into the air space, violently striking the top plate and tending to cause the breaker to jump. In so doing, there is a danger that the top plate may be distorted or that an opening between this and the oil tank may be caused through which oil can be forced. This, if nothing worse ensues, may reduce the oil content to a dangerous level. It is a requirement of design that, after fault clearance, there shall be no permanent distortion of the tank or top plate and this is the subject of check during short-circuit proving tests. As the pressures transmitted to the structure are impulsive, a certain flexibility in the structure is not a disadvantage,

provided permanent distortion is not caused. For this reason, cast-iron or similar material is rarely used in modern breaker construction.

Both rectangular and circular tank constructions are used with equal success. Some designers favour the circular construction because of its greater strength for a given weight of material and the need for a single welded seam only, whilst others favour a rectangular tank which can be made equally strong, but requires more material. Those who favour this construction point to a greater volume of oil at or near the two outer phase arcing areas in plain-break circuit-breakers. In the light of present-day testing, either form can be accepted with confidence.

Steps must be taken in circuit-breaker design to prevent a build-up of pressure within the enclosure by operations in close succession. A vent is therefore located in the expansion chamber above oil level and is so designed that it restricts the emission of oil and yet allows free passage for gas. This is usually accomplished by an arrangement of baffle plates, clay pebbles or steel marbles.

The vent should, in general, be connected to a vent pipe which discharges clear of live parts, preferably right outside the switch cubicle or housing at a point away from an operator who may be in close proximity at the moment of discharge. In medium sized switch houses (say up to 250 MVA) it is usual practice to allow venting into the switch room. For higher powers, the vent pipes may be taken out through the walls of the room, either separately or via a common header pipe, and exhausted to atmosphere. In the latter case, a non-return valve must be fitted at each junction of vent pipe and header to prevent the discharge from one breaker passing into another.

There are several constructional features in the design of tank and top plate structures which are important. Among these are tank linings and phase barriers, avoidance of obstructions within the top plate, magnetic break-up of top plates for the heavier currents, tank-to-top plate joint, and the provision of adequate bolting between tank and top plate.

In a three phase tank, phase barriers are always provided. In some designs, these barriers are continuous while, in others, they are in two parts with a central slot. In the former, the contact lifting crossbar is at the upper end of the moving system, while in the latter, the crossbar is placed at the lower end. It is common practice to line the inside of the tank and the phase barriers with an insulating material such as "Elephantide".

The design of the top plate in most modern circuit-breakers is in the form of a box or dome, rectangular or circular to suit the tank design and of welded steel construction. This formation provides the expansion chamber above oil level and houses the operating link mechanism for connection to the external operating gear. As far as it is possible, the top plate should have a uniform section, avoiding the introduction of pockets or projections which may set up unequal distribution of oil flow and tending to restrict the mass return of the oil after its first movement. For current ratings of 800 amperes and above it is necessary to break up the magnetic circuits to prevent local heating. In many cases it is usual to weld non-magnetic inserts in between the poles for the sake of economy, but this demands careful workmanship in order not to introduce weak points in the top plate. In other designs the box type top plate has been cast in aluminium

alloy, while in one for heavy current at medium voltage, the top plate has been formed out of a block of densified wood (see Figs. 6-5 and 6-6).

The greatest importance must be attached to the tank-to-top plate joint, and to the number and size of the bolts securing the joint. Two forms of joint are evident, (a) in which there are two machined surfaces butting or (b) in which there is a gasket or packed joint. But whatever the form, it must be capable of preventing the emission of flame, oil or gas. The number and size of the fixing bolts (usually high tensile steel) must be related to the stresses set up during fault clearance when there is a tendency for the tank and top plate to part company and for the bolts to become elongated, rendering the joint useless. As this elongation may be so slight as to be undetected by ordinary observation it is important that attention is given to this aspect of the design.

To this stage no mention has been made of contact design, except to note the problem of contact "grip" as in Fig. 6-3. It is convenient to segregate discussion on contacts into two groups, i.e. those used in what are known as "plain-break" oil circuit-breakers and those which are associated with arc-controlled breakers. The first of these is a type which, very largely, is used only in the voltage range 400-600 volts and although designs do exist for voltages up to 11 kV, most oil circuit-breakers for voltages 3·3 kV and upwards now employ some means of arc control. Here it will be

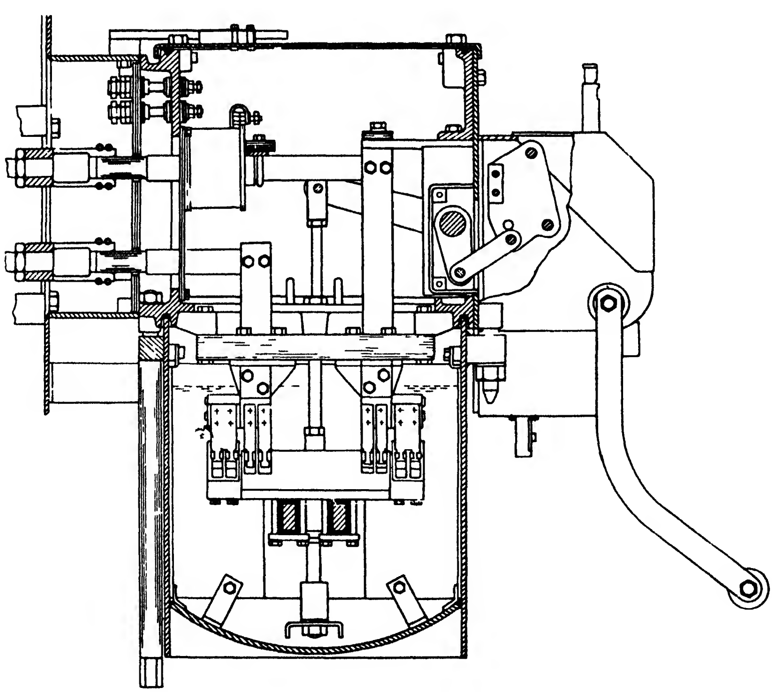


FIG. 6-5.—*Low-voltage oil circuit-breaker with wedge and finger type contacts. (Johnson & Phillips Ltd.).*

assumed that the division is on this basis and each type will be considered in turn.

The plain-break oil circuit-breaker is one in which the process of interrupting the current is achieved simply by separating pairs of contacts under oil without any special attempt to control the arc other than by increasing its length until it is extinguished. In principle this type is that already shown in Fig. 6-4 and test evidence shows that the gap between the fixed and moving contacts at which arc extinction occurs depends on the arc current and recovery voltage. Thus the performance can be described as variable and in general, very many more short-circuit tests, at the design stage, are necessary than in types where greater control of the arc is attempted.

Fig 6-5 shows, in cross-section, a typical low-voltage plain-break oil circuit-breaker employing contacts of the wedge and finger type, which are

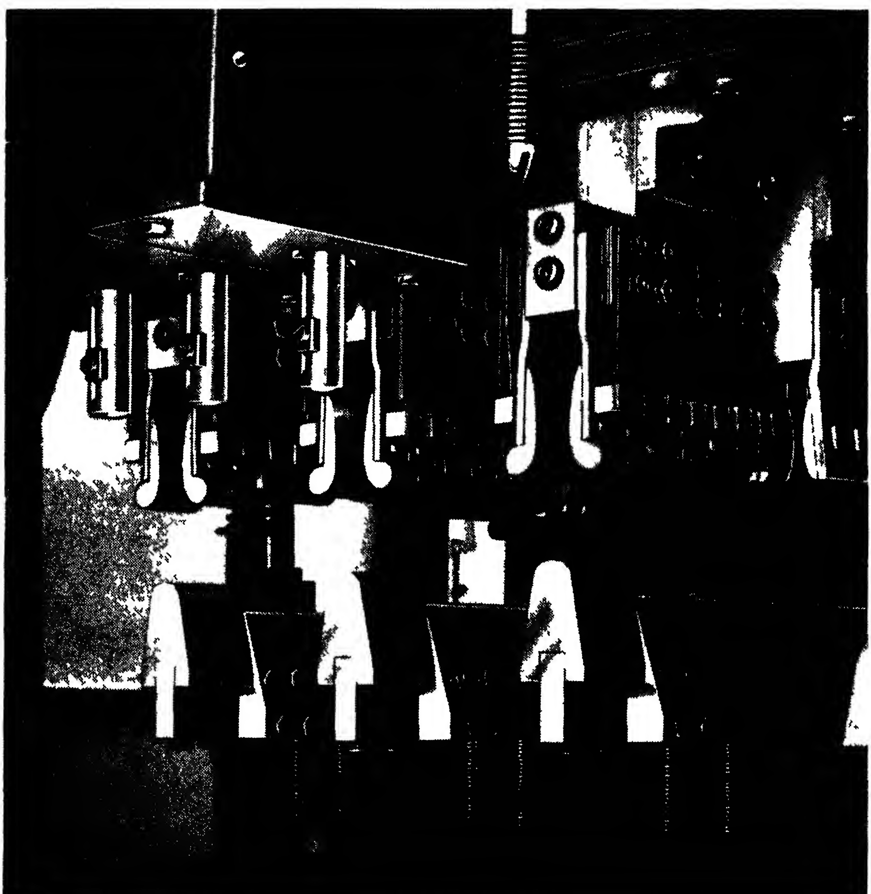


FIG. 6-6.—*Close-up view of wedge and finger type contacts.*

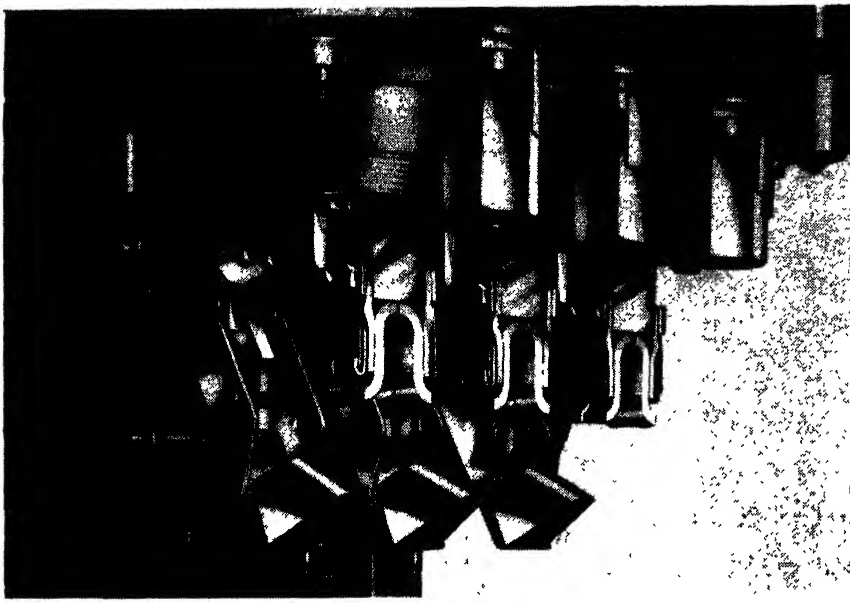


FIG. 6-7.—*Wedge and finger type contacts on single-break circuit-breaker (Johnson & Phillips Ltd.)*

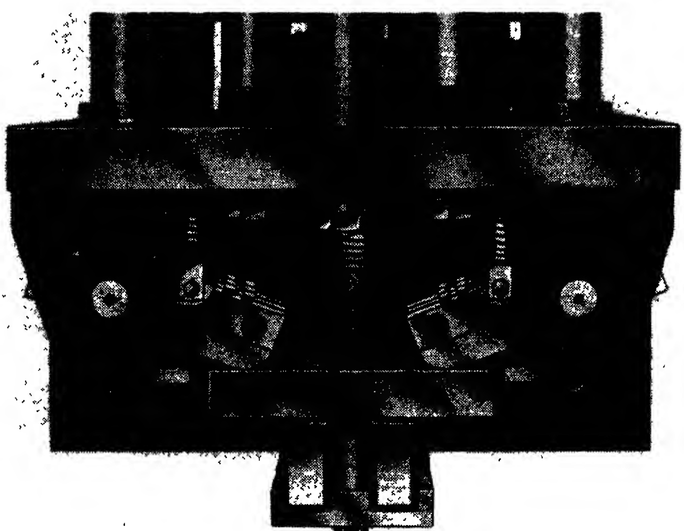


FIG. 6-8.—*Butt type finger contacts (Johnson & Phillips Ltd.).*

perhaps the most popular form. This type of contact assembly is shown in Fig. 6-6 in more detail and from this it is seen that the moving contact comprises a wedge-shaped crossbar with extended wedge-shaped renewable arcing contacts at its extremities. These wedge contacts engage in the closed position with a series of self-aligning fingers under spring pressure, the number of fingers being related to the normal current rating of the breaker.

This form of contact has several advantages. It is easy to assemble, is of unit construction, lends itself to self-alignment, and the contact pressure of the fingers is relatively constant over a range of wedge positions. Contact pressure is further assisted by mutual attraction of the fingers under electromagnetic influence, i.e. contact "grip". Increased life may be obtained for certain types of breaker—such as those used with electric furnaces where repeated switching is the rule—by the use of arcing contacts faced with one of the tungsten metals.

In early designs of the wedge and finger type contact, both the wedge and the fingers had plain flat surfaces because it was assumed that the normal current to be carried would be more easily achieved by having the components in contact over the face area. It is now known, however, that unless exceptional care is taken in the preparation of flat surfaces, contact will not be made over the whole area but, more likely, only at a number of high spots, thus leading to contact chatter and overheating.

The practice was adopted, therefore, of making one or both of the contacting surfaces slightly curved to provide a "line pressure" contact and under proper conditions of pressure, this enables more than 100 amperes to be carried per half-inch of line contact.

In passing it may be noted that Fig. 6-5 shows an example of a circuit-breaker where the supporting plate for the fixed contacts comprises a block of densified wood, a design feature introduced to break up the magnetic circuit in heavy normal current designs. Note too that instead of the more normal through insulators with copper stems in solid rod, the through conductors here comprise copper strips taken straight through the top plate.

The wedge and finger type contacts can also be adapted for use in single-break circuit-breakers (as opposed to the double-break design in Fig. 6-5) and one example of this is seen in Fig. 6-7. In this form of single-break design, current has to be carried at the hinged point and great care has to be taken in the development of current-carrying elements at this point to ensure adequate area and pressure at all times. In other designs of single-break circuit-breakers, the hinged point is eliminated by moving a sliding contact, as will be noted later.

A form of contact in which the troublesome problem of "grip" is eliminated is the rolling butt type, one example of which is shown in Fig. 6-8.

This type of contact has another advantage in that spring loading of the fixed contacts gives valuable assistance at contact separation, but it must be remembered that the closing mechanism has to overcome this pressure when closing the breaker. There is some limitation to the normal current ratings which can be contemplated with butt contacts but in the design in Fig. 6-8, with a multiplicity of fixed contacts, each individually spring-loaded and making line contact with a moving contact in the form of a solid block, ratings up to 1200 amperes have been achieved.

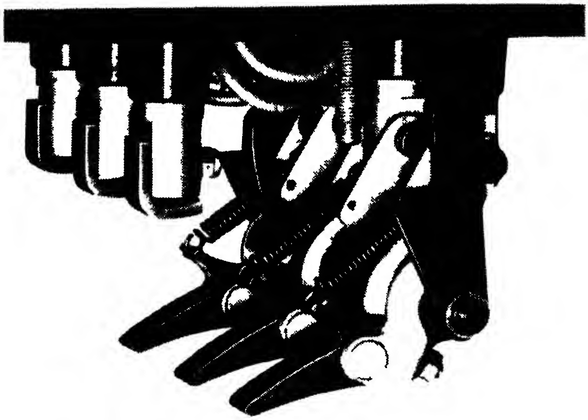


FIG 6-9.—*Contact system of the single-break butt type (The General Electric Co Ltd.)*

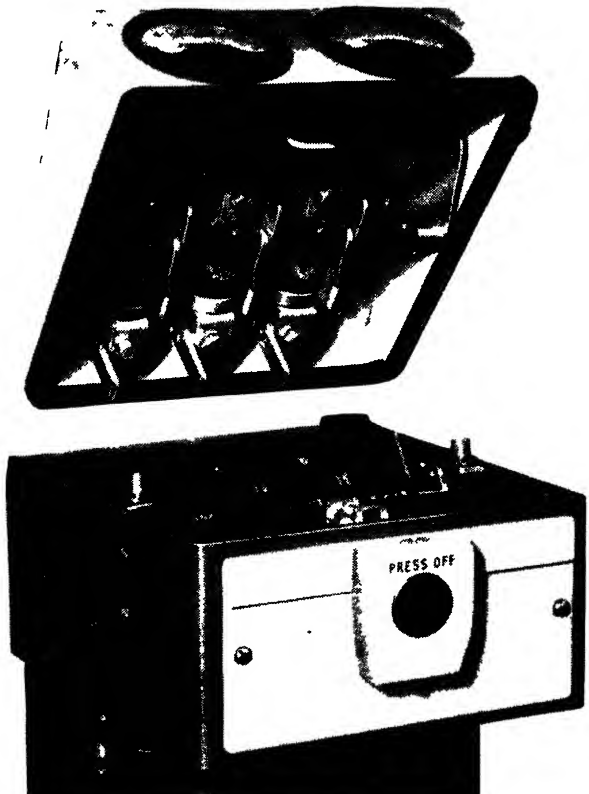


FIG. 6-10.—*Industrial circuit-breaker with plug-in isolating unit and h.r.c. back-up fuses (The General Electric Co. Ltd.).*

An interesting example of the use of rolling butt type contacts is that shown in Fig. 6-9 which is a system used in a single-break industrial oil circuit-breaker up to 150 amperes up to 660 volts.

Of limited breaking capacity (5·2 MVA at 415 volts) this circuit-breaker can be used on systems of higher fault value by using h.r.c. back-up fuses which form an integral part of a plug-in isolator as shown in Fig. 6-10.

For heavier currents, say 2 000/3 000 amperes, it is possible to use an entirely different design such as that in which the main current carrying contacts are of a laminated brush type, as shown in Fig. 6-11. Here the brushes form the fixed contacts while the moving contact is a solid copper plate carried on a copper channel base. Both the brush contacts and the plate contact are silver plated. Separate arcing contacts are provided, these comprising a solid copper block (carried on the channel crossbar) mating with a spring-loaded brass plunger to give butt contact. A view of a complete breaker employing contacts of this type is shown in Fig. 6-12 and it is of interest to note that here again the terminal stems comprise laminations of copper bar.

Whatever form of contact is used, it is important to see that low contact resistance is obtained and maintained, bearing in mind that resistance varies inversely as the pressure. Further, it is equally important to remember that copper oxidises when working at reasonably high temperatures and that copper oxide has a very high resistance. Once this oxidisation has started a vicious circle ensues; the increase in contact resistance causes further heating which, in turn, causes further oxidisation, leading to more heat, and so on. These effects are particularly important in heavy current circuit-breakers which usually operate for long periods in a closed state at

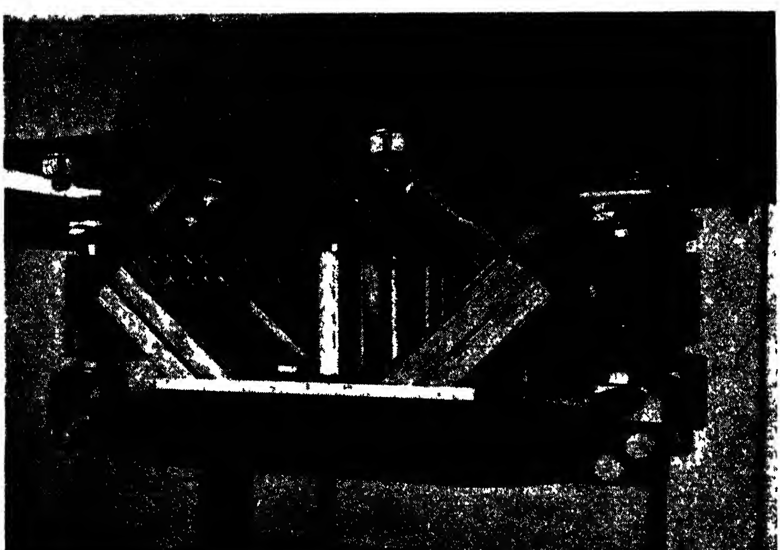


FIG. 6-11.—*Laminated brush type main contacts with butt type arcing contacts (Johnson & Phillips Ltd.).*

temperatures somewhere near the design limit. It emphasises the importance of maintaining contacts in a clean condition, a condition which can be helped by the simple expedient of opening and closing a circuit-breaker a few times at regular intervals. This process is further assisted where line contacts are used as these are self-cleaning to a high degree

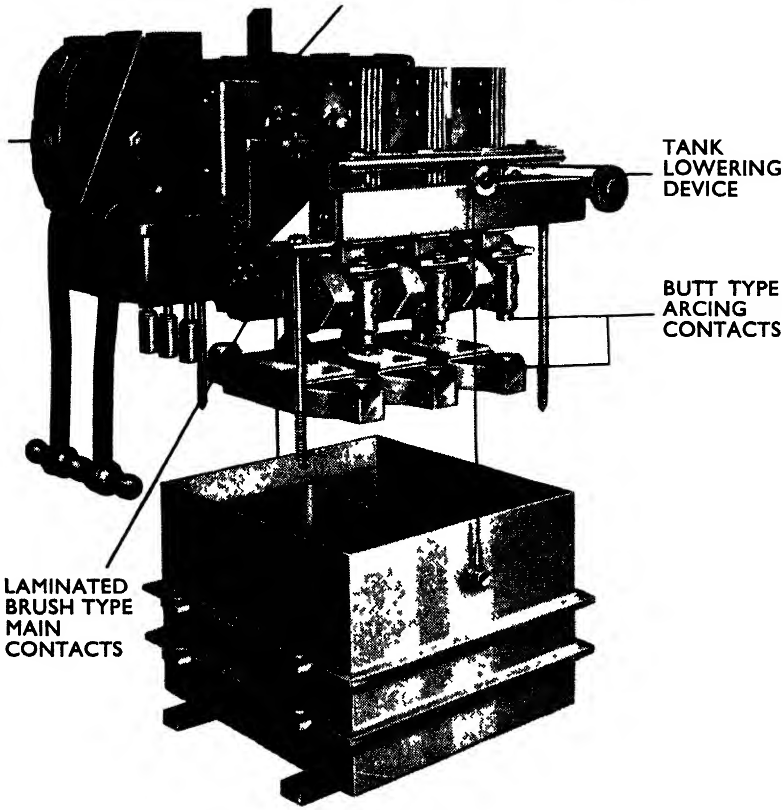


FIG. 6-12.—3 000 *ampere l.v. circuit-breaker with brush type main contacts* (*Johnson & Phillips Ltd*)

In order to lessen contact resistance, silver plating or facing may be resorted to. This is generally done for the heavier currents (1200 amps and above) but only on the main contacts because any silver applied to arcing contacts would soon be destroyed under arcing conditions. Silver so applied not only reduces initial resistance but also does not appreciably increase.

As indicated earlier, plain-break circuit-breakers can be used for voltages 3·3 kV and above (up to 11 kV they would be similar to the l.v. design in Fig. 6-5 but with porcelain or paper bushings for the through terminals and improved clearances) but as the voltage increases, so does the necessary contact gap for circuit interruption increase and plain-break designs tend to become very large. Instead therefore the oil circuit-breaker in which the

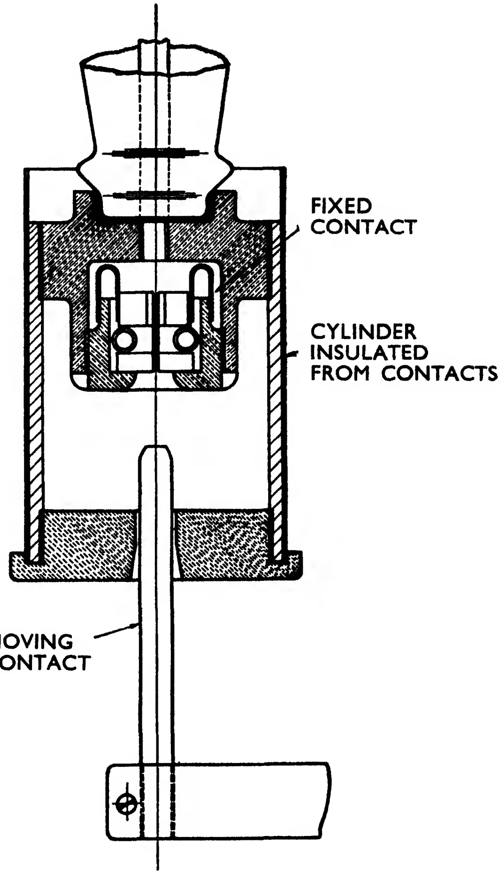


FIG. 6-13.—*Typical early explosion pot.*

arc is controlled is preferred, providing for arc extinction with a relatively short contact gap at all currents and being consistent in operation.

Perhaps the earliest form of arc control device was the so-called "explosion pot", a typical example of which is shown in Fig. 6-13. Here, a strong shell of insulating material is arranged to enclose the fixed and moving contacts, the latter comprising a stud moving vertically into and out of a circular cluster of fixed finger contacts and through a relatively close fitting throat at the lower end of the pot. When the contacts part, the gas generated by the arc produces a very high pressure in the space enclosed by the pot. The effect of this pressure combined with effects produced by the streams of vapour flowing turbulently into the arc tends to cause arc extinction, but if this is not achieved while the moving contact is still within the pot, it occurs immediately after the stud leaves the pot due to the axial high velocity blast which is released through the orifice as the stud leaves. This blast completely envelopes the arc and the effect of the release of pressure

was such as to cause the designers to give the name "explosion pot" to this device.

This early device functioned with reasonable satisfaction for certain values of current, although the arc energy was high. It has its drawbacks, however, when used for very small or very large currents. With the former, long arcing times were experienced, while with the latter the pressure set up within the pot limited its practical use. These limitations led to the development of more effective means of control and to the many forms of present-day device in which venting is provided for pressure control and relief. This may take the form of either side or top venting, but the former is more commonly used.

The introduction of the side-vented arc-control device was due to the work of the E.R.A. in its researches into circuit-interruption and an original patent No. 366998 granted to the E.R.A. has formed a basis for most of the devices in use today. This basic design is shown typically in Fig. 6-14 and comprises a chamber to completely enclose the contacts (except for the side vents or ports) and automatically filled with oil from the breaker tank.

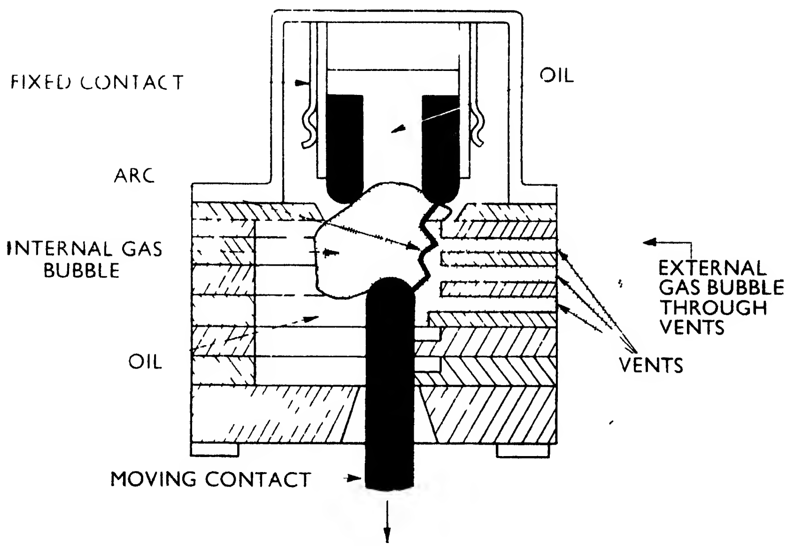


FIG. 6-14. -*Basic side-vented arc-control device.*

The arc, as indicated in Chapter II breaks down the oil to form a gas and the pressure set up within the chamber forces the gas and arc products out through the uncovered vents, displacing and lengthening the arc as shown. At each current zero, the arc is extinguished and fresh oil enters the chamber and at some point in this process, the insulation value between the fixed and moving contacts will be sufficiently high as to prevent a restrike.

At the "contact-closed" position, the vents are covered by the moving contact but as soon as this has moved to a point just beyond contact separation the first vent is uncovered and if the vent area is such as to ensure sufficient

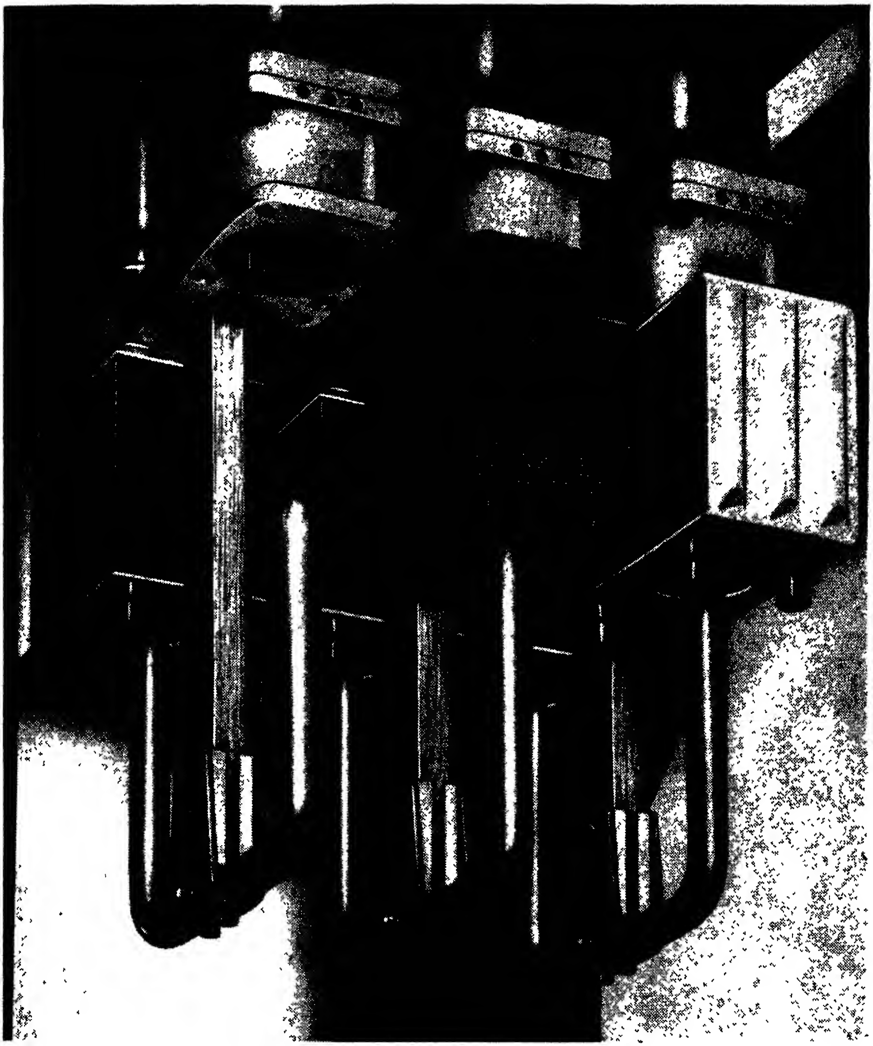


FIG. 6-15.—*Contact system and arc-control devices (one removed) in* 11 *kV* 350 *MVA oil circuit-breaker (Johnson & Phillips Ltd.).*

pressure rise, the arc may be extinguished at this point. If not, further movement will uncover the next vent to assist in arc extinction. Any further vents provided are usually regarded as a safety precaution to prevent dangerous pressures rises should for any reason a particularly long arc be drawn but tests prove that in most devices, extinction occurs at all values of current before the tip of the moving contact leaves the arcing chamber.

As will be seen in a number of devices to be illustrated, only one vent has been provided and this has been proved satisfactory.

Arc control devices are applied with equal success to both double and single-break circuit-breakers and an example of the former has been noted in Fig. 6-2 while a close-up view of the contact system and arc-control devices is given in Fig. 6-15. For the purpose of this illustration one arc-control device has been removed to show the circular configuration of fixed contacts, each contact backed by a helical spring. This type of contact, like the wedge and finger type described earlier, is subject to contact "grip". Unlike the butt type however, the arc at contact separation is generally maintained between the tip of the fingers and the tip of the moving contact. Burning at these points therefore leaves the main contact surface clean for good contact in the fully closed position. In butt types, the opposite is often the case, i.e. the points at which burning occurs are also the main points of contact in the fully closed position.

Fig. 6-15 shows an interesting development in that a fibreglass port or vent shield is fitted to each arc-control device (one is shown in position on the right hand pole in the illustration). The purpose of this shield is to permit the use of porcelain bushings on breakers up to 800 amperes for 350 MVA 11 kV duty instead of bakelised paper Normally the latter are used to obtain the greater mechanical strength necessary to withstand the "loop" forces (see Fig. 6-4) although electrically porcelain is much preferred. By fitting these port shields to take the thrust of the arc products emerging from the ports, it has been found possible to relieve the stresses on the bushings and thereby employ porcelain instead of paper.

Typical short-circuit test results relating to this design have been given in Chapter V covering values from $2\frac{1}{2}$ to 100 per cent of rating, coupled with single phase tests to check on the effect of unbalanced forces within the breaker.

It will be noted that in this breaker, which is typical of many in its range, the moving contact is of solid round copper rod, the diameter being varied to suit the normal current rating, coupled with silver plating in some instances. For the higher MVA values, i.e. 150 MVA at 3·3 kV, 250 MVA at 6·6 and 11 kV and 350 MVA at 11 kV, the contacts are tipped with copper/tungsten alloy to reduce the amount of burning on "breaking" and eliminate any tendency to weld on "making".

In designs of this type, features of the tank, top plate, accelerating springs, buffering, etc. do not differ radically from those already described.

The single-break oil circuit-breaker has, in recent years, become a close competitor with the double-break type and there are many examples in successful operation. Early research into the problem of circuit-breaking revealed that in some circumstances (as for example when interrupting an earth fault) the recovery voltage at current zero in a double-break design was divided as to 85 per cent on one break and only 15 per cent on the other. It was argued therefore that as the greater part of the interrupting duty fell on one break, why not dispense with the other and let a single-break perform 100 per cent? It has been claimed that the second break is in fact something of a handicap in that it draws an arc equal in length to that of the more effective break thereby generating an unnecessary volume of gas. This investigation was studied by Davis and Flurscheim in 1926 and in a more recent article related to arc control devices by McNeill and Crane

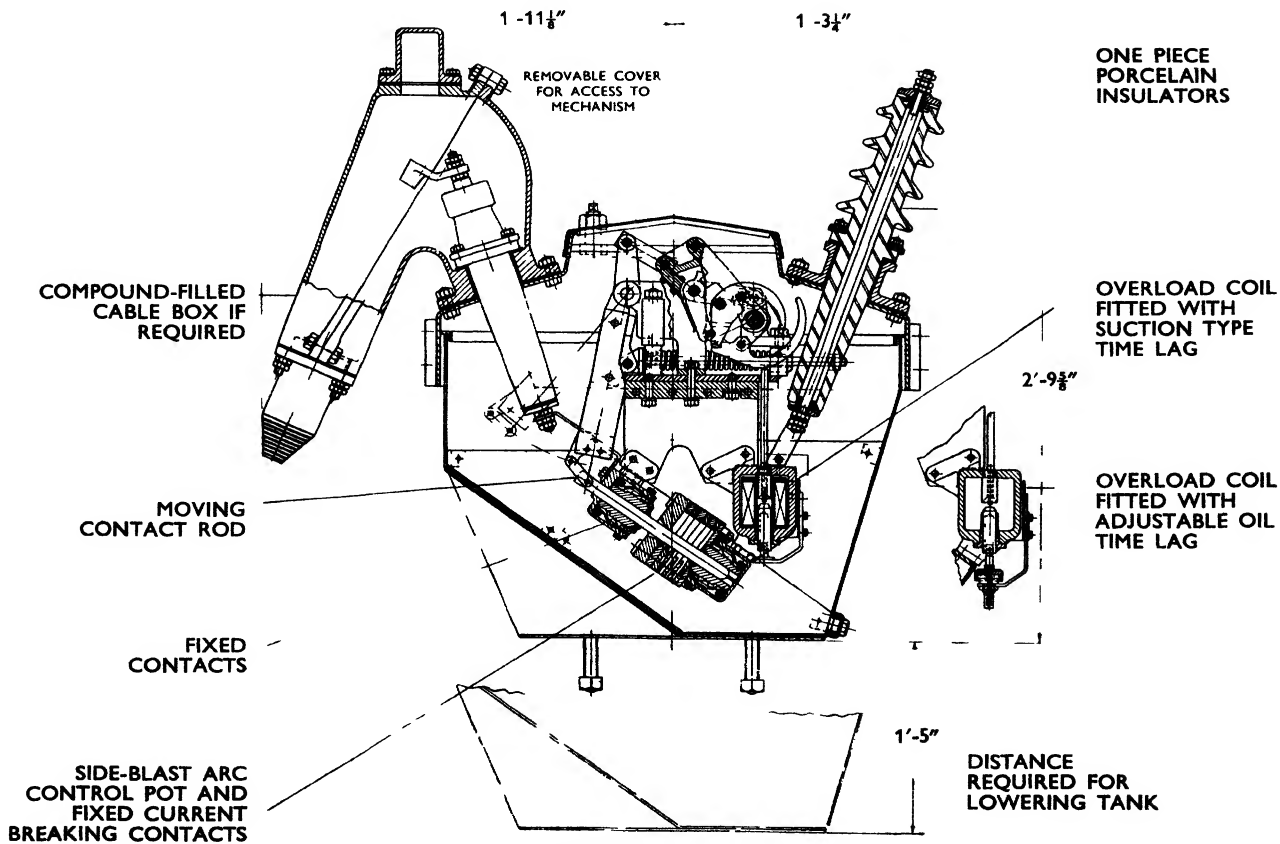


FIG. 6-16.—*Single-break oil circuit-breaker (outdoor pole mounting) with side vent arc-control device (Johnson & Phillips Ltd.).*

in 1954, while Crane has also considered the relative merits of double and single breaks in his book "Switchgear Principles" For our purpose here, it will suffice to be reminded that in a single-break design, the moving component is not completely isolated after opening as in the double-break and that the hinge (if used) demands very careful design to ensure good current carrying ability at this point

As a first example of a single-break design, we may consider Fig 6-16 which shows an outdoor pole-mounting circuit-breaker rated 75 MVA at 6·6 and 11·9 kV

Note how, by arranging the contact system at an angle, the depth of the tank is kept to a minimum thus reducing the volume of oil and the total weight The contact system and arc-control device are shown in more detail in Figs. 6-17 and 6-18

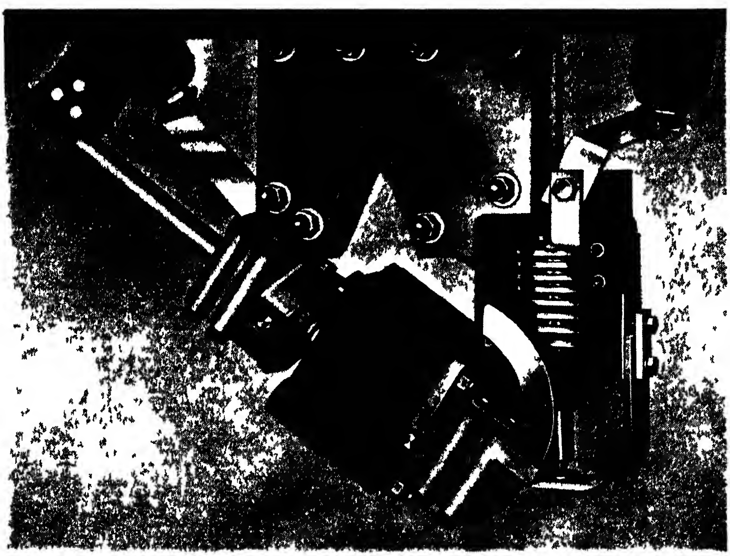


FIG 6-17 *Single-break contact system as used in Fig 6-16 (Johnson & Phillips Ltd)*

The problem of carrying current at the hinged contact is avoided in this design by adopting a system of fixed non current-breaking contacts in which the moving contact rod slides but never leaves.

An example of a single-break oil circuit-breaker in which the moving contact is carried on a hinged arm is shown in cross-section in Fig. 6-19 and in detail in Fig. 6-20

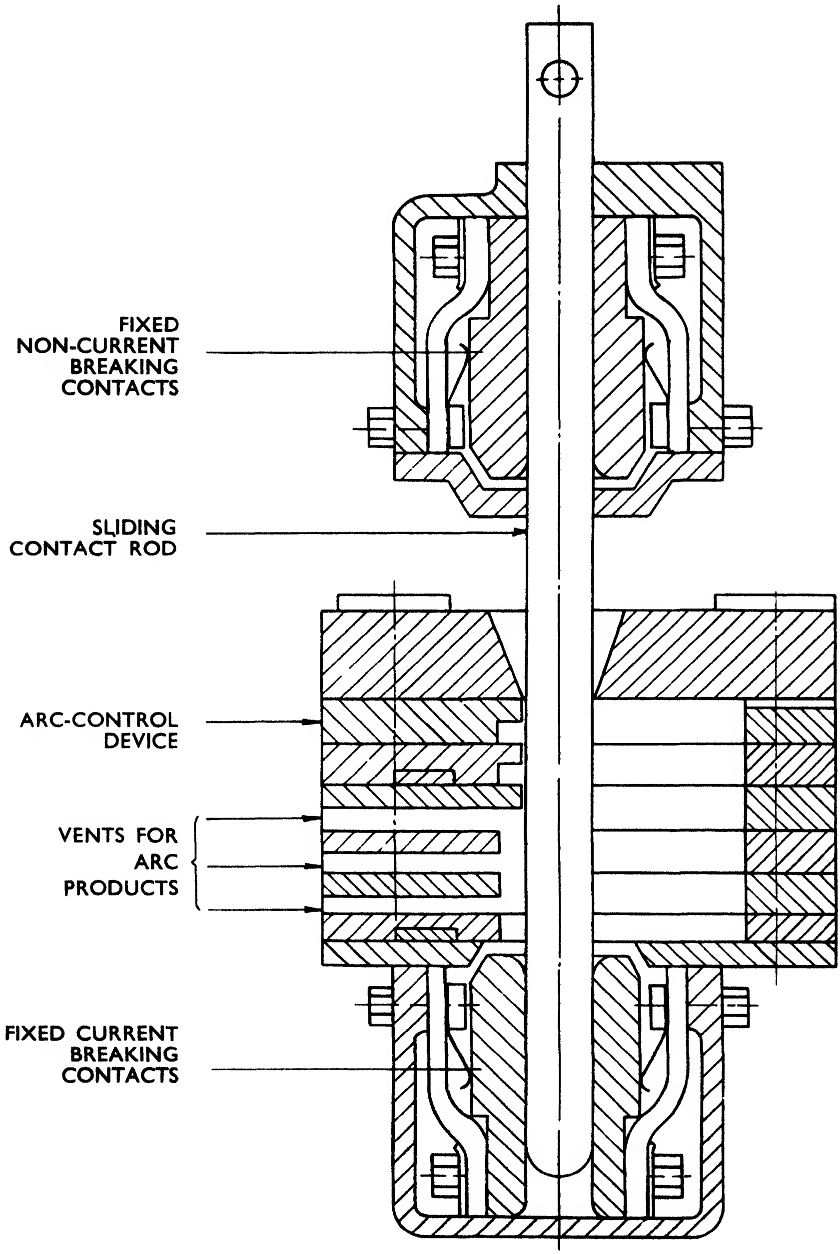


FIG. 6-18.—*Cross-section of side-vent arc-control device on single break oil circuit-breaker (Johnson & Phillips Ltd.).*

A SELF-ALIGNING SOCKET CONTACTS

B COMBINED GUIDE PIN AND GAS VENT

C GUIDE PIN

D ORIFICE SEALING WASHERS

E TOP PLATE EARTHING CONTACT

F KICK-OFF SPRING

G CONDENSER TYPE SYNTHETIC RESIN BONDED PAPER INSULATOR

H DASHPOT MECHANISM

J SELF-ALIGNING FIXED CONTACTS

K EXTERNAL FIXED LOAD-BEARING BUTT CONTACT

L MOULDED GLASS-FIBRE OPERATING LINK

M MOULDED NYLON TURBULATOR

N CURVED MOVING CONTACT

O INTERNAL MOVING LOAD-BEARING BUTT CONTACT

P INTERPHASE BARRIERS

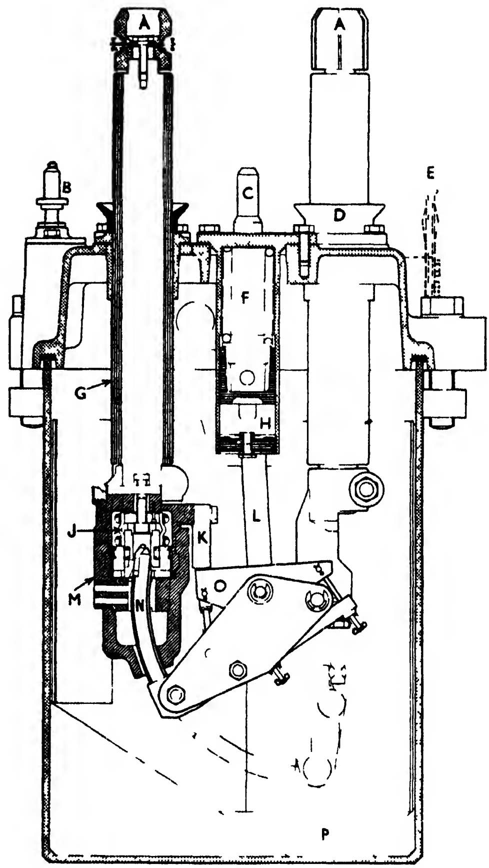


FIG 6-19 —*Cross-section of a 1 200 ampere single-break oil circuit-breaker 250 MVA up to 11 kV (A Reyrolle & Co Ltd)*

It is of interest to note that for a 1 200 ampere rating, additional load-bearing contacts of the butt type are incorporated. These contacts, marked K and O in Fig. 6-19, are placed *outside* the arc-control device and take no part in the interrupting duty. For lower normal currents, such additional contacts are not necessary. Current transfer to the fixed hinge-blocks is effected in this design by means of spring-loaded hinge-contacts.

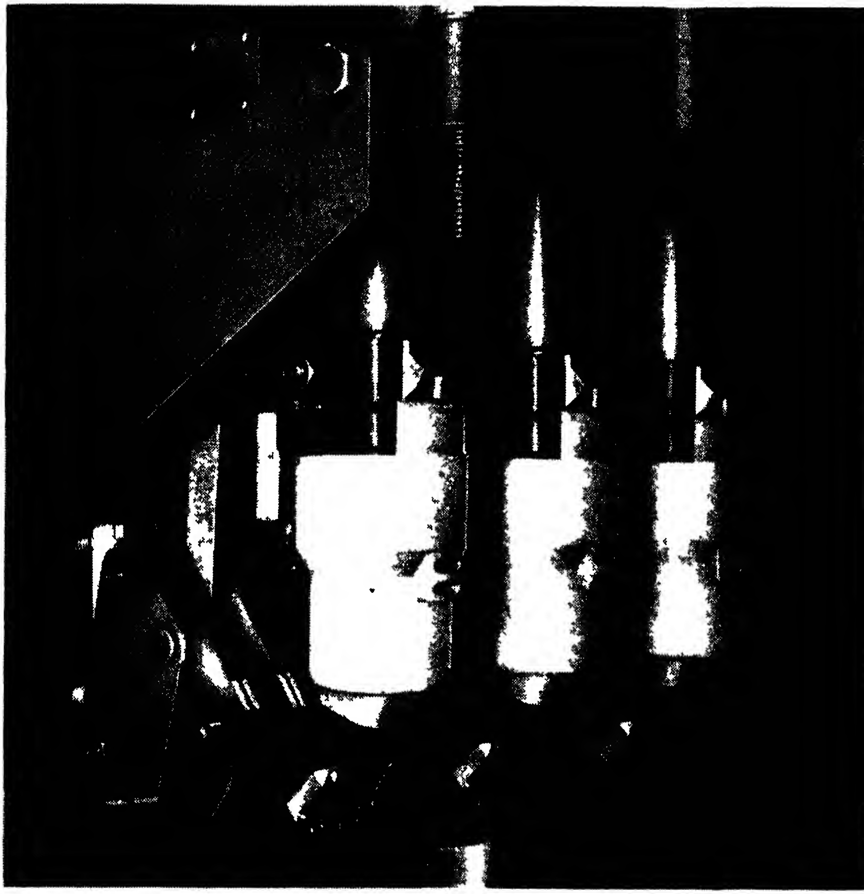


FIG 6-20 —*Single-break 1 200 ampere contact system and arc-control devices Note the load-bearing butt contacts external to the arc-control device (A Reyrolle & Co Ltd)*

The arc-control device in this circuit-breaker (as in others by the same manufacturer) is designated 'Turbulator" and is of the side-vented type operating generally on the principle previously described In this breaker, the body of the arcing chamber, shaped to suit the movement of the curved moving contact, is made in moulded nylon with fibre inserts to form the vents This principle is noted again in Fig 6-21 which shows one of six turbulators as fitted to a double-break oil circuit-breaker for 11 kV service, the insert having been removed from the arcing chamber In this design, the moulding material is a high-tensile strength phenol-formaldehyde

Fig 6 21 —*Moulded nylon body and fibre vent inserts for "Turbulator arc-control device* (*A Reyrolle & Co Ltd*)

For easy and rapid removal, the "Turbulator" arc-control device has a breech-block fitting We shall note another example of this form of arc-control device later in this chapter and in Chapter VII

In another design, shown in Fig 6-22, pressure adjustment is provided at the hinged type fixed contact This breaker and others by the same manufacturer, employs arc-control devices of a type described as

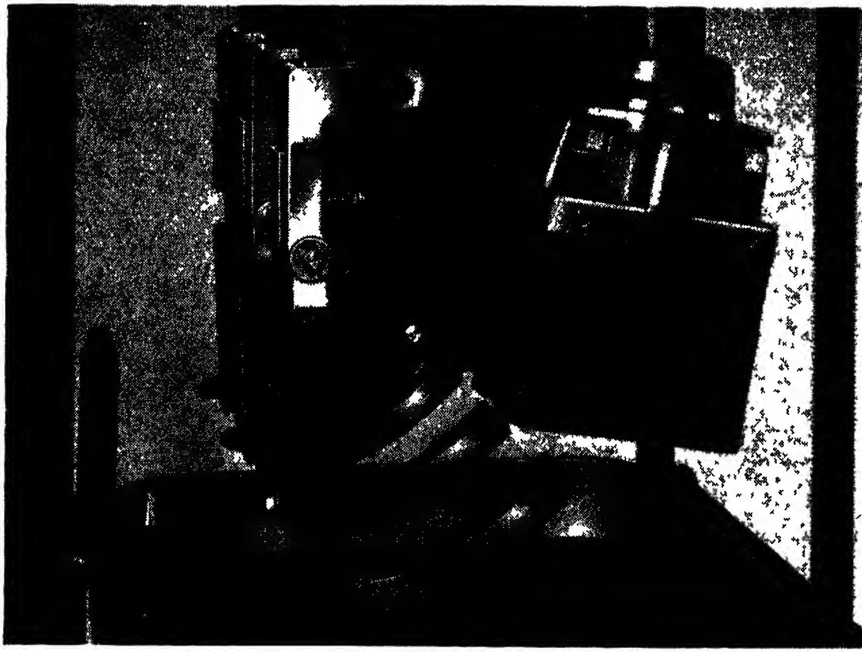


FIG 6-22 *Single-break contact system and arc-control devices (Switchgear and Cowans Ltd)*

"compensated-pressure flow" in which the vent orifices are automatically adjusted (in area) depending on the magnitude of the fault current. Fig. 6-23 shows in more detail how this is achieved, noting that for low values of current, the vents are almost closed as at (a), due to the spring loading being greater than the generated pressure within the device. Here the arc follows a sinuous path due to the oil vapour pressure and flow At higher currents, the pressure generated within the device will be sufficient to overcome the compression spring and the stack plates will open to increase the venting areas as shown at (b). The arc will now be nominally straight with distortion into the stack plates as the pressure is vented from the chamber. In the design illustrated spring-loaded butt type contacts are employed but for heavy current applications, a cluster assembly of fixed contacts together with external reinforcing contacts, is used.

In the designs so far noted, and others which we shall note later for higher voltages, the arc-control devices are fixed to the circuit-breaker bushings and the moving contact is withdrawn on opening. There is, however, a design in which the arc-control devices form part of the moving contact system, as shown in Fig. 6-24, and with the breaker in the open position, the devices are isolated from the system

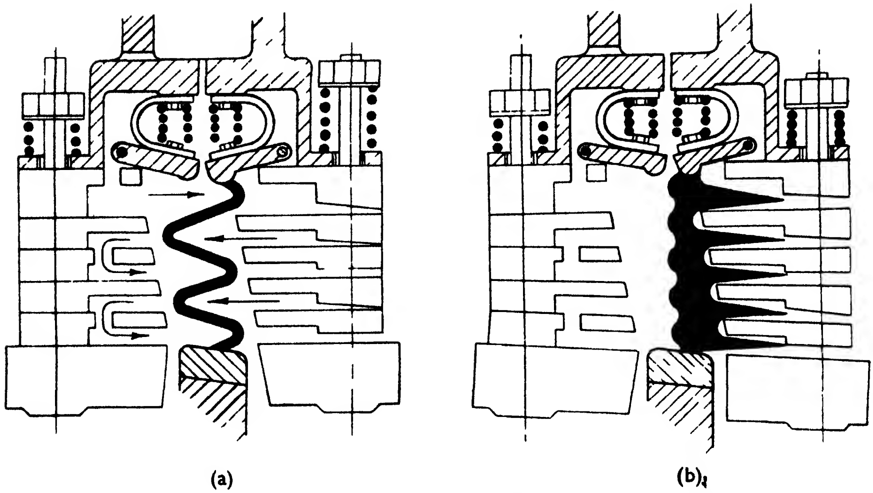


FIG. 6-23 —*Compensated-pressure flow arc-control device*
(*a*) *Opening on low currents* (*b*) *Opening on high currents*
(*Switchgear and Cowans Ltd.*).

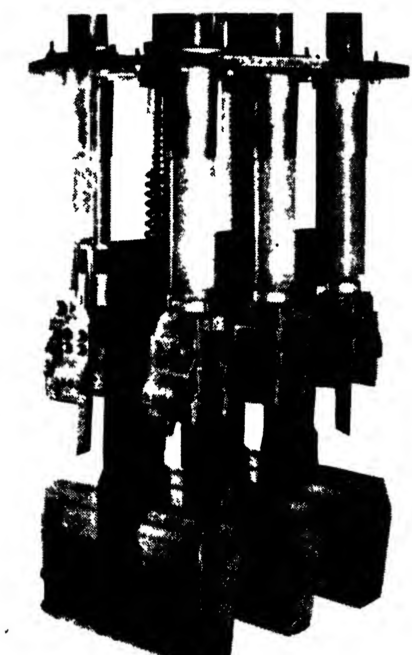
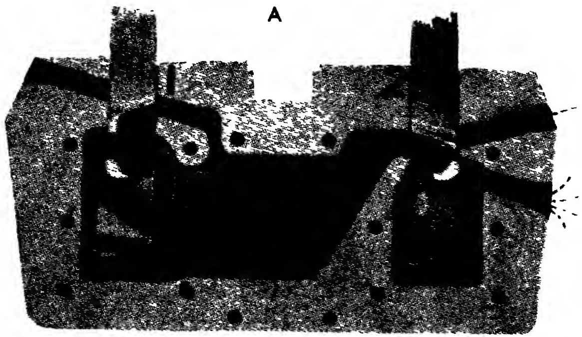


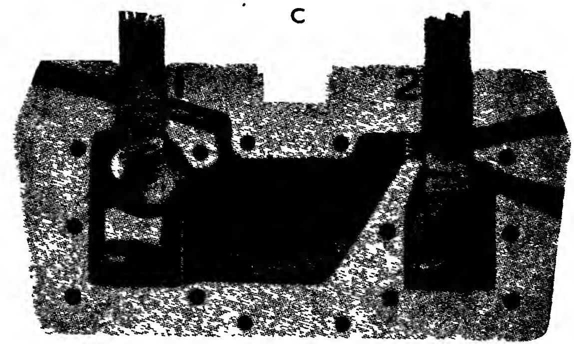
FIG. 6-24.—*Contact system using "Caton Arc-Trap" on moving contact of circuit-breaker* (*Yorkshire Switchgear and Engineering Co. Ltd.*).

A



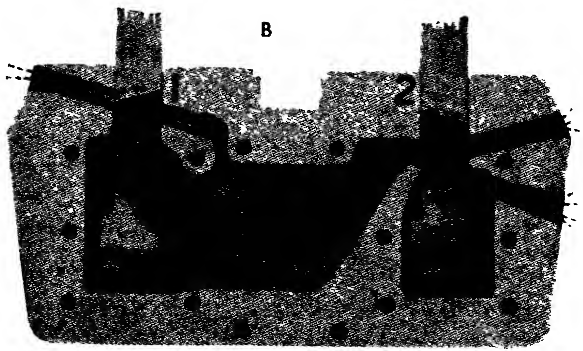
No. 1 Electrode leads by ¼ cycle producing constricting pressure around No. 2

C



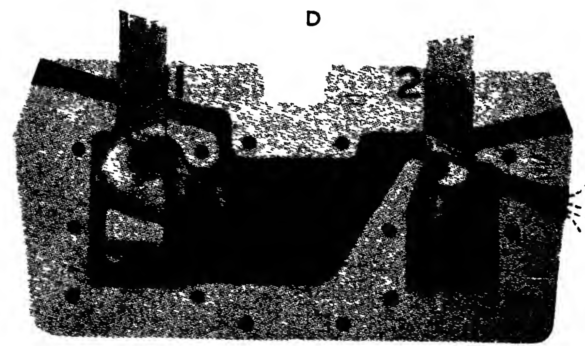
Arc severed at current zero by high pressure clean oil

B



No. 2 Electrode parts contact.
Arcing restricted and displaced by pressure

D



Arc Trap scoured by exhausting pressure and rapidly refilled with clean oil

FIG. 6-25.—*Operating sequence of the "Caton Arc-Trap" (Yorkshire Switchgear and Engineering Co. Ltd.)*

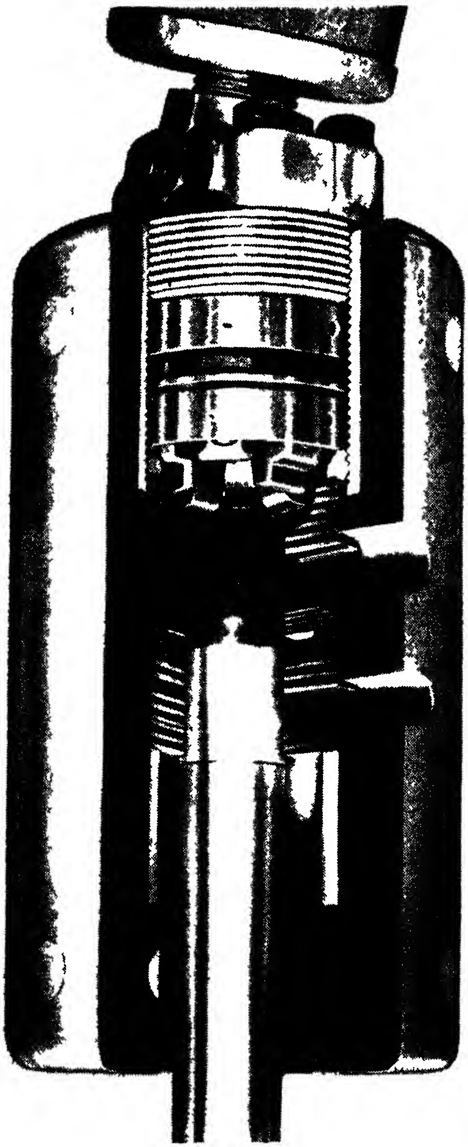


Fig 6-26 --*Broken sectional view of "Natural Flow" arc-control device and contact system (The English Electric Co Ltd)*

This illustration shows that only the arcing contacts are operating within the arc-control device (designated "Caton Arc-Trap") and that the main current-carrying contacts are placed outside so that burning on the arcing contact surfaces has no effect on the main contacts.

The principle on which this arrangement functions is demonstrated in Fig. 6-25, it being noted that there are two sets of interconnected arcing contacts within the oil reservoir formed by the device and these co-operate with electrodes on the fixed contact system. Electrode 1 is foreshortened so that the initial arc is drawn here in advance of that at electrode 2. These electrodes operate through very limited apertures which develop and control the point where a concentration of high-pressure oil is allowed to constrict the arc at 2. At a natural current zero, the oil is forced at high velocity into the arc path and in sweeping away the conducting vapour, interposes a barrier of high dielectric strength. The ideal condition for interruption in this device is that the arc at electrode 1 should commence immediately following a current zero, in which case extinction usually occurs at the next zero. If arcing commences at or about current maximum, another loop might be necessary to develop the necessary pressure for extinction.

In a range of arc-control devices employed in the English Electric designs of oil circuit-breaker, a series of labyrinths are shaped to form "passages" and "blind alleys", the former to control the flow of oil and gas created by the pressure of an arc, the latter to cause high pressure pockets to be set up during the arcing period. This design is shown typically in Fig. 6-26 and, because of the foregoing, it is given the name "Natural Flow".

The fixed contact assembly comprises both main and arcing fingers, the latter tipped with special arc resisting metal. Because the arc is generally drawn between the moving contact and those finger contacts that are situated on the outboard side of the electro-magnetic loop, uneven burning of the arcing finger contacts occurs. Provision is therefore made whereby the complete contact cluster can be rotated to bring the least affected contacts into the arcing plane and thereby even out the burning. The number of vents varies from one to three depending on the duty and voltage. Fig. 6-27 shows this type of arc-control device as fitted in a 33 kV outdoor circuit-breaker with all phases in one tank. One device has been sectioned and the circuit-breaker has opened to the position when the first arc vent has been uncovered.

In its basic principle as an interrupting device, the outdoor oil circuit-breaker differs little from its indoor counterpart, the major difference arising out of the need to make the unit completely weatherproof and to ensure that moving linkages associated with the closing mechanism are adequately protected so that any tendency to stick due to weathering is eliminated. The exposed end of the circuit-breaker bushing will have a porcelain weather shield with rain sheds which also give an extended creepage path from the live terminal at the upper end to the earthed flange at the circuit-breaker top plate. The shape of these sheds may vary depending on the atmospheric conditions anticipated, a popular form being that known as "anti-fog". The bushings themselves are generally of the bakelised paper condenser type and are often oil-filled. The design is of a specialist nature often outside the scope of the switchgear engineer or user for whom this book is intended but typical examples will be seen in some later cross-sectional illustrations, e.g. Figs. 6-32 and 6-44.

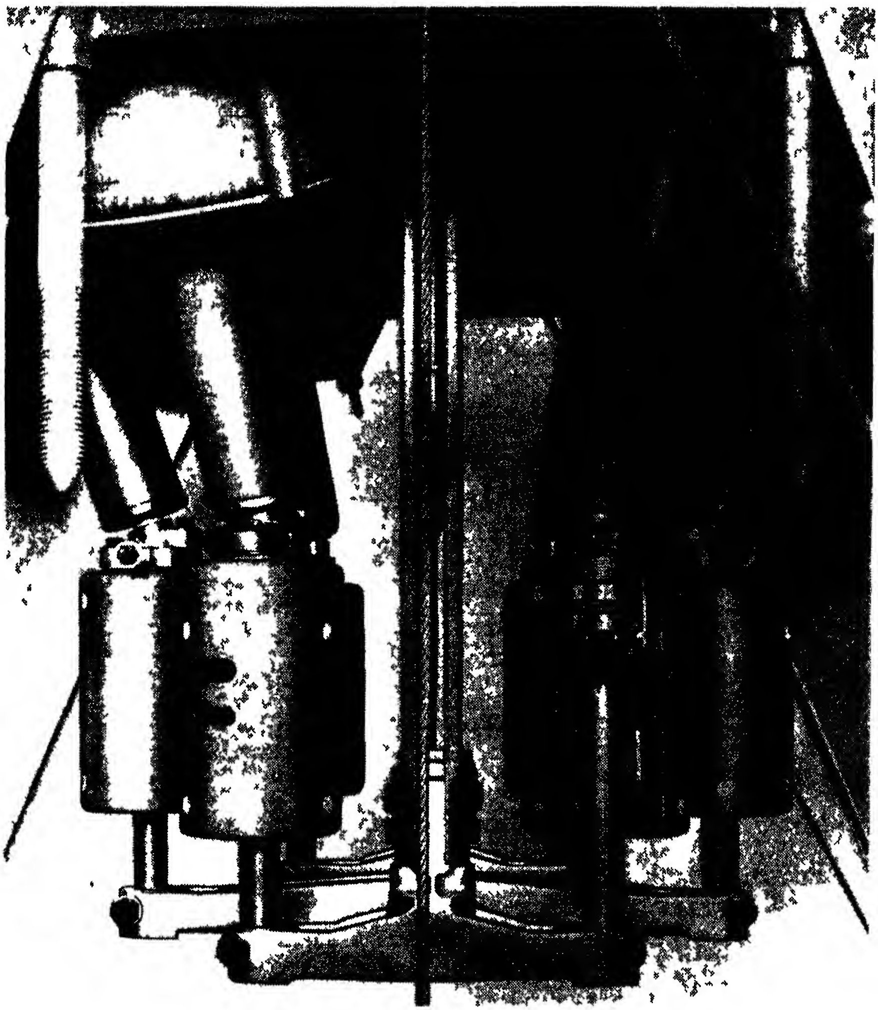


FIG 6-27 —*Contact system of 33 kV outdoor circuit-breaker showing arc control devices (one in section), with contacts opening*
(The English Electric Co Ltd)

Outdoor breakers are available for most voltages in the range 6·6 to 380 kV and, up to about 88 kV, they are generally arranged as frame supported units, the frame also carrying the operating mechanism At higher voltages, the breaker becomes too large for this form of mounting and it is necessary to stand the tank directly on the ground In the frame mounted arrangement, access to the contact system for inspection and maintenance is obtained by lowering the tank by means of a self-contained mechanism To gain access

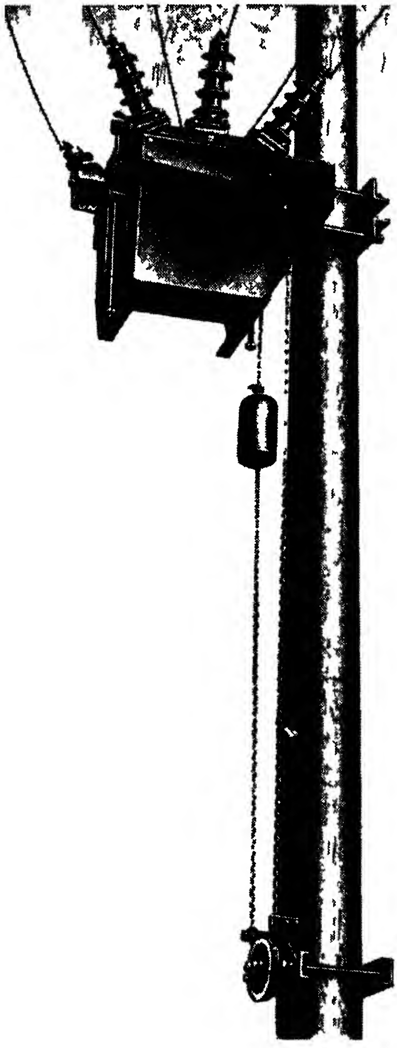


FIG 6-28 —*Pole-mounted outdoor oil circuit-breaker with auto-reclose mechanism (Johnson & Phillips Ltd)*

to a floor-mounted breaker, a manhole or access port must be provided but before entry can be made, the oil must be drained off or pumped away Access by this means will be noted in a later illustration

At voltages of 6·6 kV and 11 kV, the oil tank is usually common to all three phases with suitable phase barriers built-in At 33 and 66 kV the design may have one common tank or a separate tank for each phase, while for higher voltages a separate tank for each phase is essential

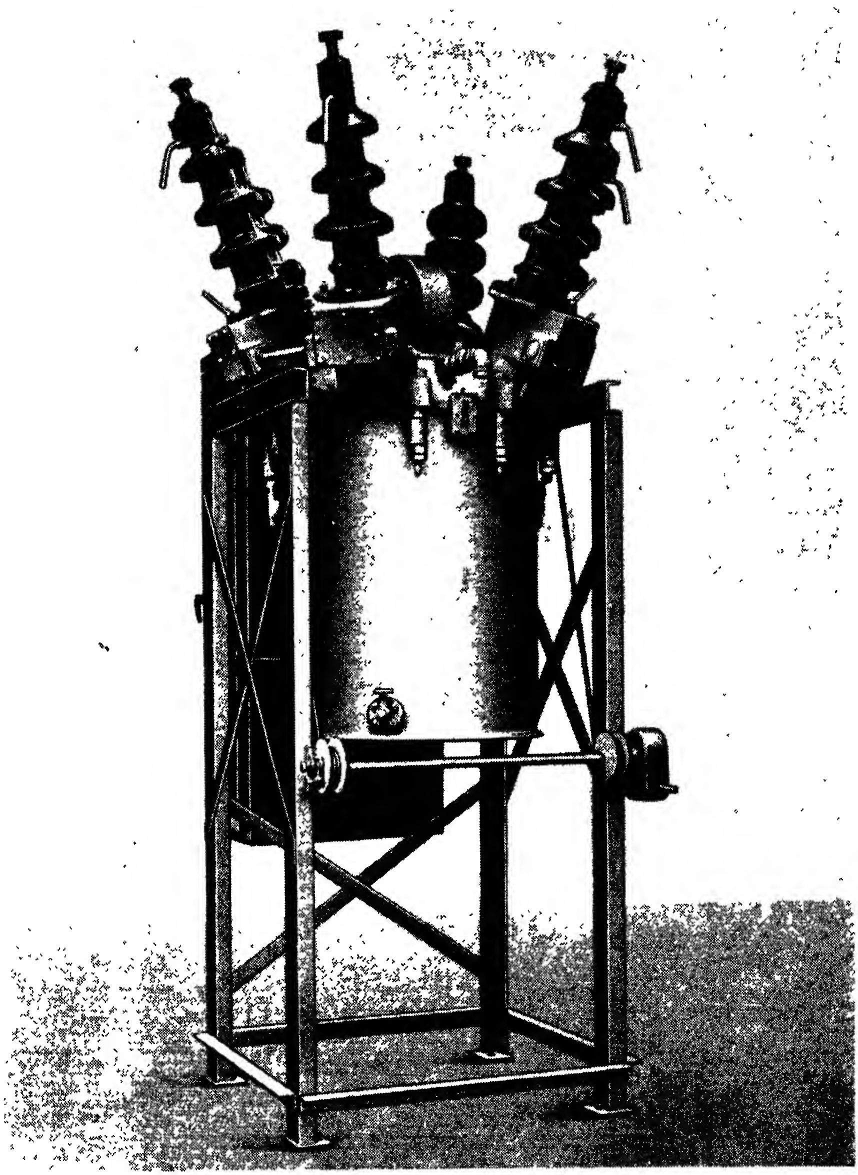


FIG. 6-29.—33 *kV outdoor oil circuit-breaker of the single tank type and frame-mounted (Brush Electrical Engineering Co. Ltd.).*

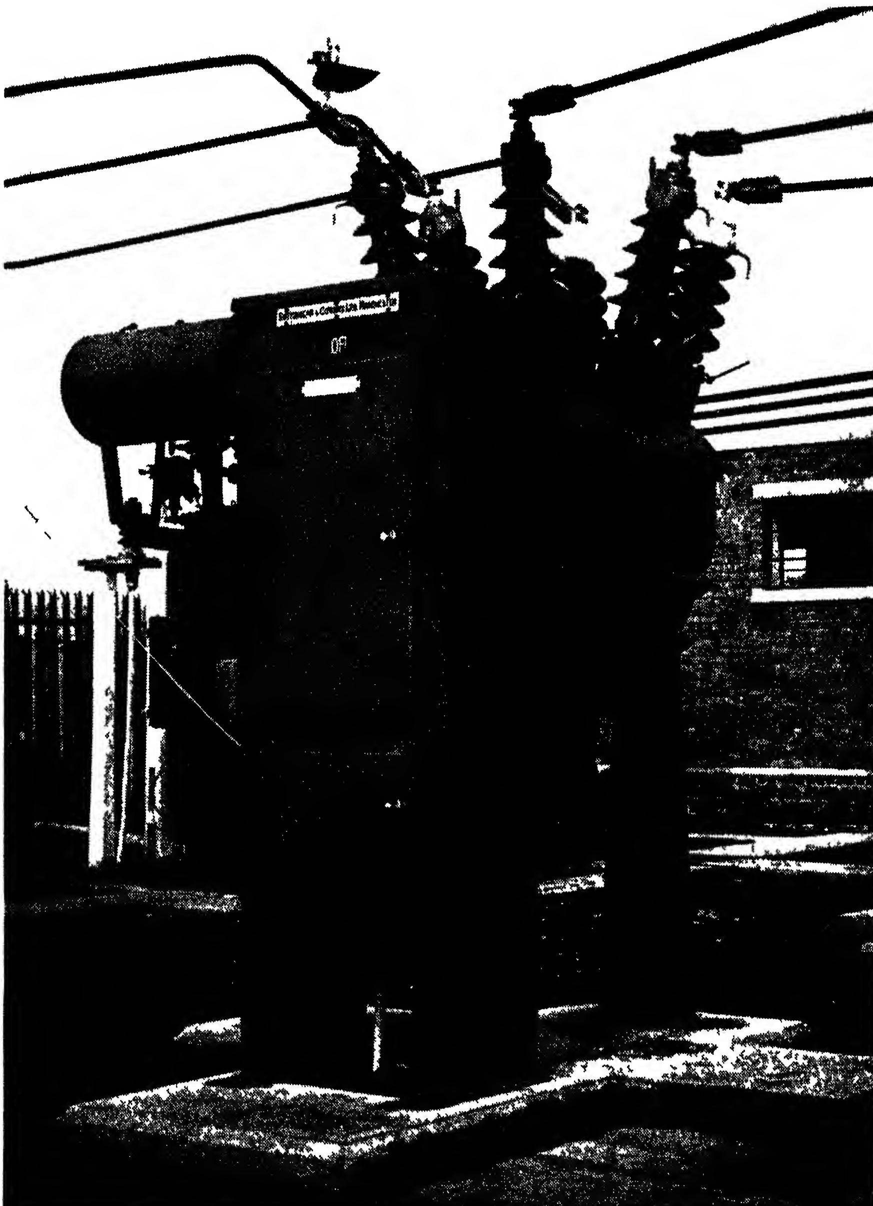


FIG 6-30 —33 *kV outdoor oil circuit-breaker of the single tank type and frame-mounted (Switchgear & Cowans Ltd)*

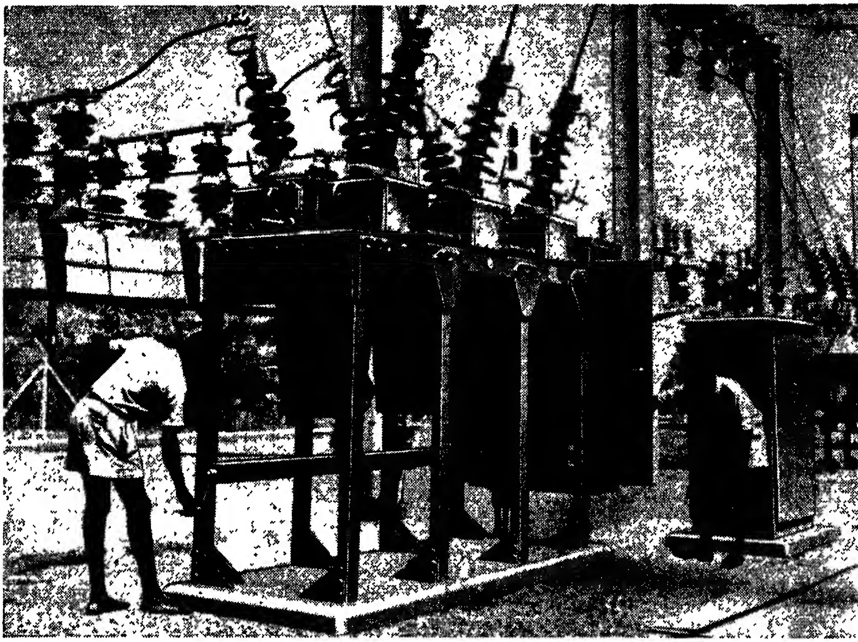


FIG. 6-31.—33 *kV outdoor oil circuit-breaker of the three tank type and frame-mounted. Installed in a switching station at the Owen Falls Power Station (The General Electric Co. Ltd.).*

An alternative form is a circuit-breaker designed for pole mounting and used for rural distribution at 6·6 or 11 kV. Such a circuit-breaker has already been noted in Fig. 6-16 while in Fig. 6-28 this breaker is shown mounted as in service.

This breaker is shown arranged for automatic reclosure by means of a spring-cushioned weight seen carried on an endless chain. The length of the chain determines the number of possible reclosures but normally these are limited to three. The time between tripping and reclosure may be varied between 10 and 50 seconds. When it is required to trip the circuit-breaker manually, this is achieved by pulling up the weight until a projection on the chain lifts a trip catch. Alternatively a simple hand-closing mechanism can be provided with a lever handle at suitable height above ground.

Because of the much greater clearances required in air between live terminals than are necessary under oil, outdoor circuit-breaker bushings are angled, thus reducing the tank size. This feature will be noted in later illustrations.

From these illustrations it is interesting to note that where a common tank is employed for all three phases, one design (Fig. 6-29) employs a circular tank and the breaker is of the double-break design, while another (Fig. 6-30) has a rectangular tank and the breaker is of the single-break type. This latter design is shown in more detail in Fig. 6-32.

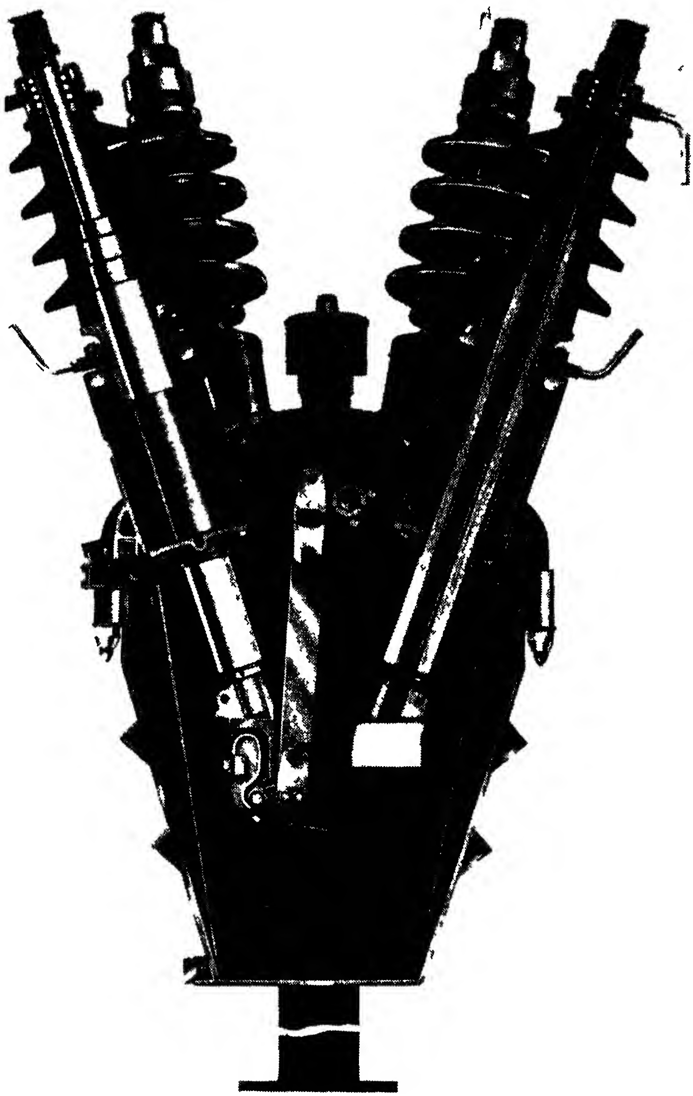


FIG. 6-32 —*Cross-section through 33 kV single-break oil circuit-breaker as Fig 6-30 (Switchgear & Cowans Ltd.).*

In the design shown in Fig 6-31 where three separate tanks are employed, the tanks are again rectangular and the breaker is of the double-break type as shown in Fig. 6-33. A reduction in the oil content is made by tapering the two short sides of the tank towards the bottom

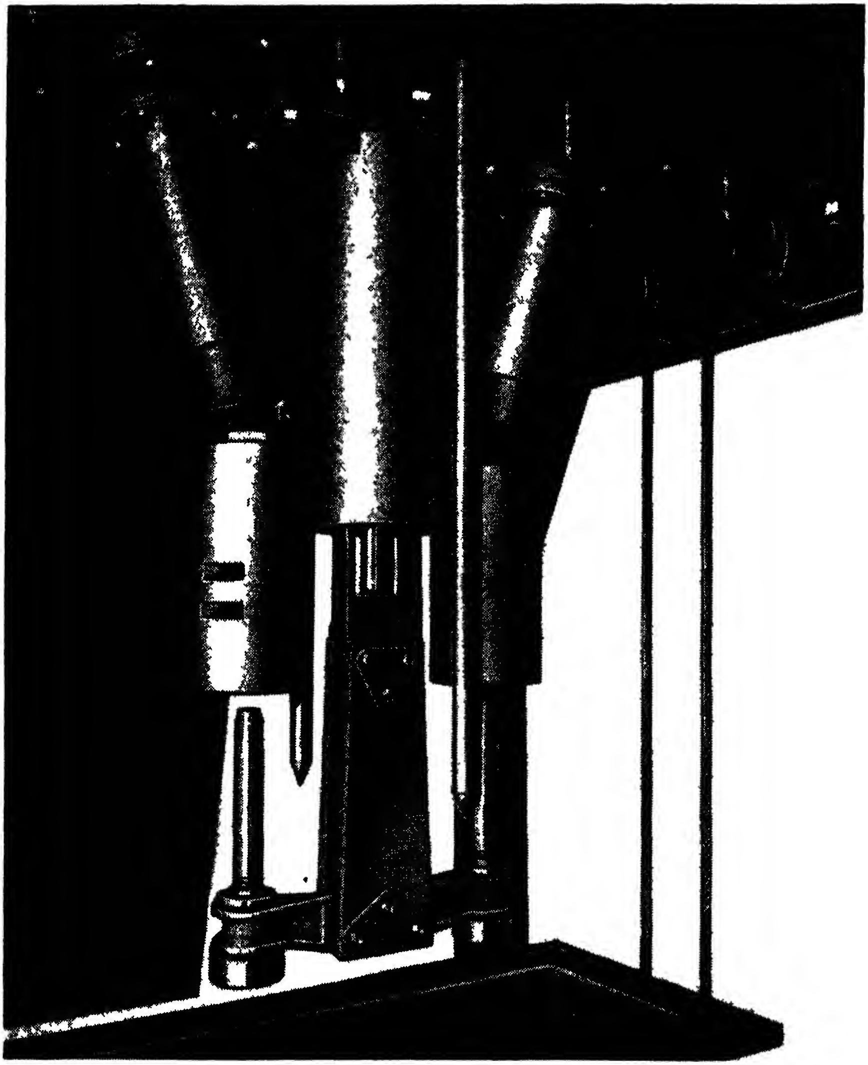


FIG 6-33 — *Contact system of one phase of the circuit-breaker shown in Fig 6-31 (The General Electric Co Ltd)*

In another example of 33 kV outdoor pedestal mounted circuit-breaker, all three phases are contained within a single circular tank as shown in Fig 6-34 An interesting feature of this design is that by the use of cast

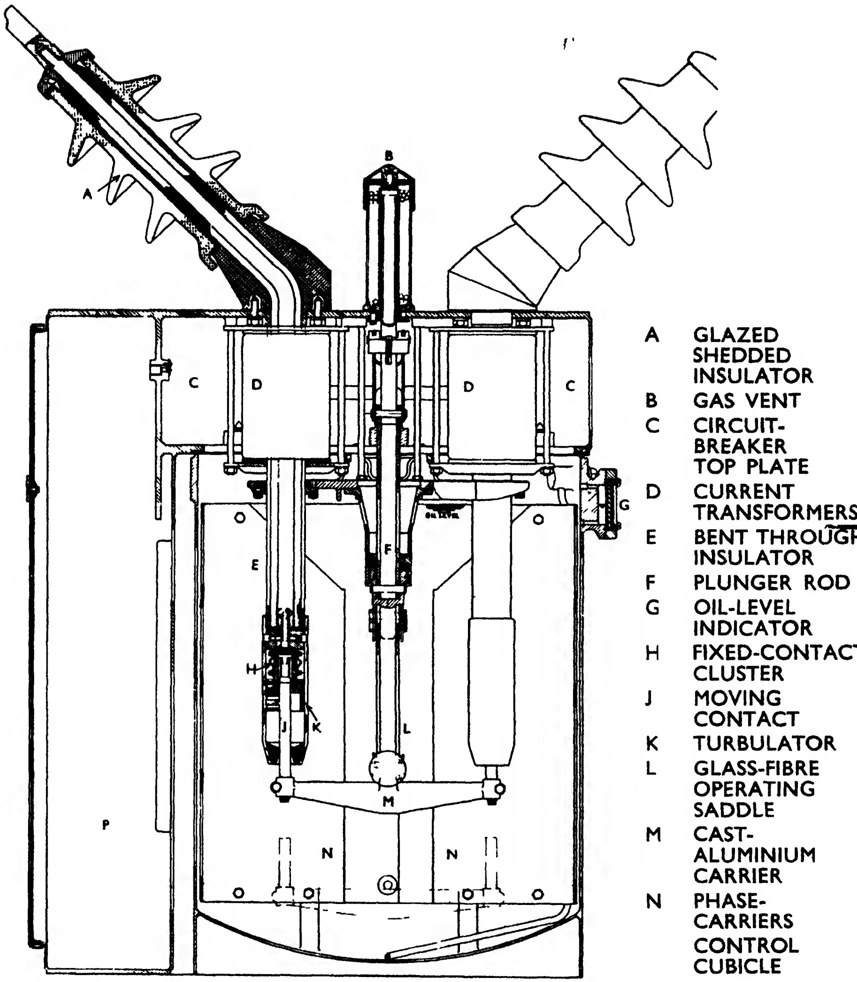


FIG. 6-34.—*Cross-section of 33 kV outdoor circuit-breaker for pedestal mounting (A. Reyrolle & Co. Ltd.).*

epoxy resin mounting flanges for the bushings, bent continuous conductor stems can be employed as Fig. 6-34 shows. This allows the circuit-breaker dimensions to be kept down to a minimum as that part of the conductor stem within the tank is vertical instead of being angled in line with the external bushing. The bend in the conductor stem enables any required pitch circle dimension of the terminal points in air to be obtained.

Another interesting feature is that the "Turbulator" arc-control devices are made of resin-bonded glass-fibre as noted in Fig. 6-34 and in more detail in Fig. 6-35.

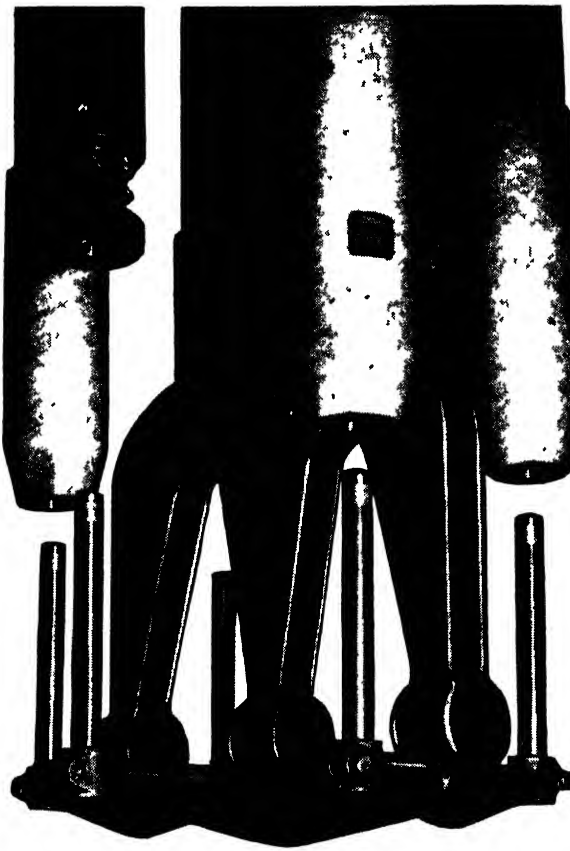


FIG. 6-35.—*Fixed and moving contact system and "Turbulator" arc-control devices as in the circuit-breaker shown in Fig. 6-34 (A Reyrolle & Co. Ltd.).*

The use of resin-bonded glass-fibre for the outer casings of arc-control devices arises out of the need to employ a casing strong enough to withstand the high internal pressure set up within the device when interrupting high short-circuit values and yet employ a reasonably thin wall casing on account of space.

Permali Ltd. have recently made available such glass-fibre products not only for arc-control devices but for blast tubes, cylinders and storage vessels in air-blast switchgear In a technique known as filament winding, glass rovings in parallel bands are wave wound on to a mandrel so as to produce a helical pattern in which the helix angle can be adjusted to suit a particular requirement Epoxide or polyester resins are normally employed to impregnate and bond the glass rovings, which are then heat cured. Some examples of arc-control device casings in resin-bonded glass-fibre are shown

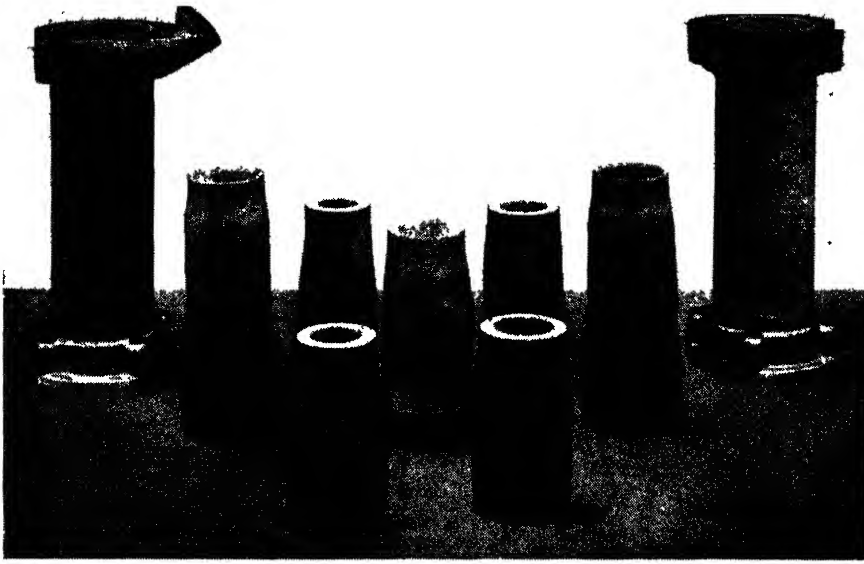


FIG. 6-36.—*Examples of helically wound glass-fibre arc-control device casings (Centre group) (Permali Ltd.)*

in Fig. 6-36 In this illustration, the two parallel diameter casings to the left and right of the group are, in fact, the tanks for continental type low oil content circuit-breakers and in these designs, the arc-control device is a separate sub-assembly housed within the tank.

Reduction in the quantity of oil is made possible in a 66 kV outdoor oil circuit-breaker as shown in Fig. 6-37 by employing a single-break contact system where the moving contact moves horizontally, shown in detail in Fig. 6-38.

This effectively reduces the depth of tank required.

In another design the three separate tanks are oval shaped, again with the purpose of reducing the oil volume. This design is shown in Fig. 6-39, and the tank shape is clearly indicated by the configuration of the top plate seen in Fig 6-40 which shows additionally the moving contact system, arc-control devices, with resistor stacks mounted at sides, and ring type current transformers mounted around the bushings beneath the top plate.

Typical of a 66 kV design employing a common tank for all three phases is that shown in Fig. 6-41.

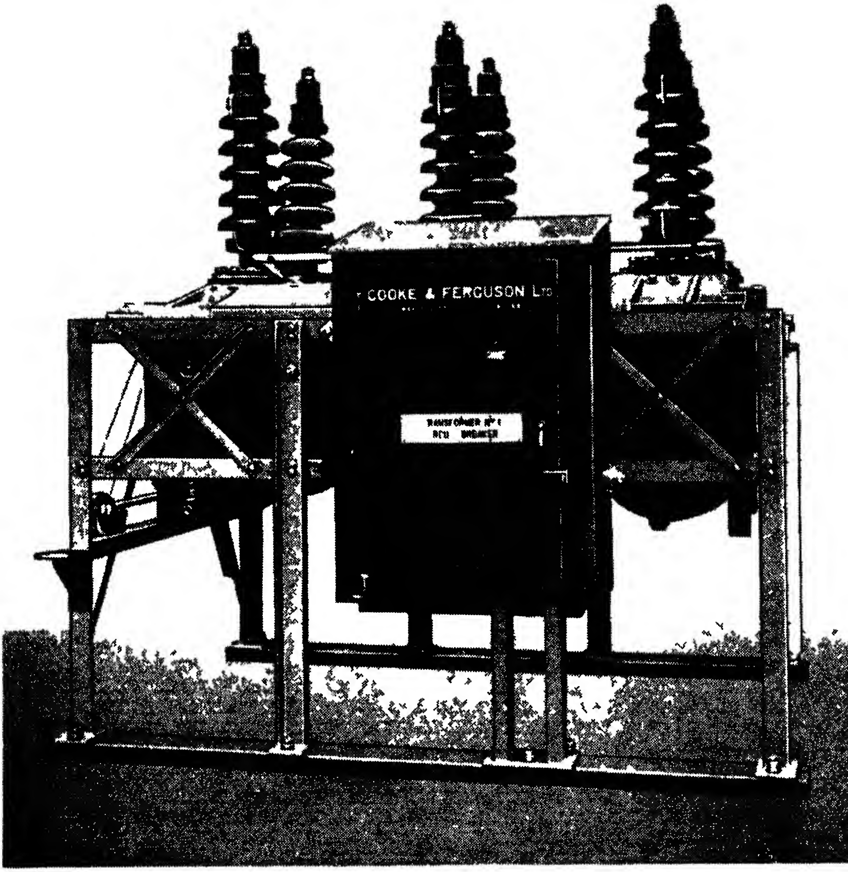


FIG 6 37 66 *kV outdoor oil circuit breaker of the three tank type and frame mounted (Crompton Parkinson Ltd)*

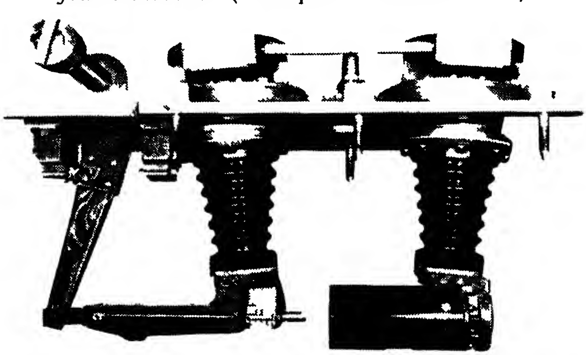


FIG 6-38 —*Horizontal single-break contact system (one phase) of the breaker shown in Fig 6-37 (Crompton Parkinson Ltd)*

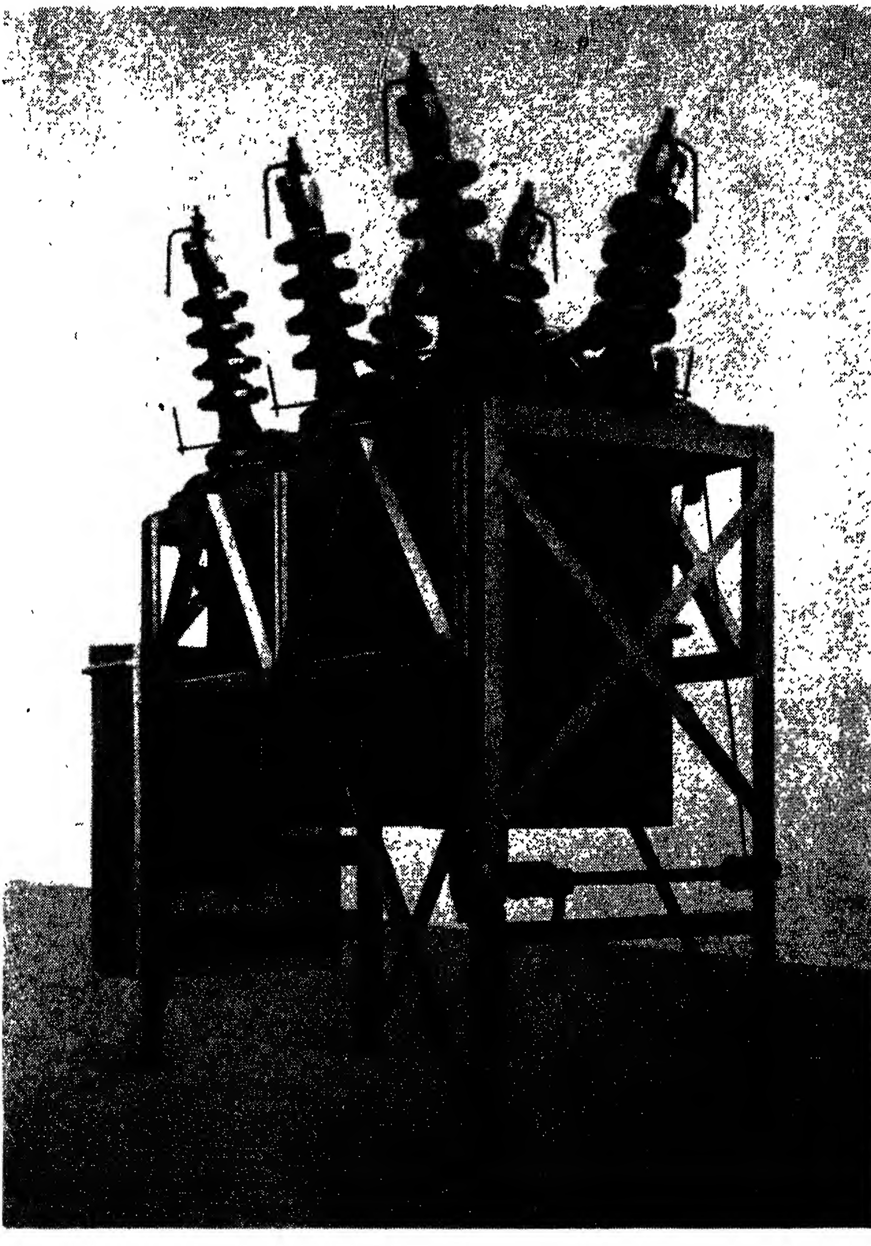


Fig. 6-39.—66/88 *kV outdoor oil circuit-breaker of the three tank type and frame-mounted (The English Electric Co. Ltd.).*

FIG 6-40 —*Single phase assembly (tank removed) of the 66 kV breaker shown in Fig 6-39 (The English Electric Co Ltd)*

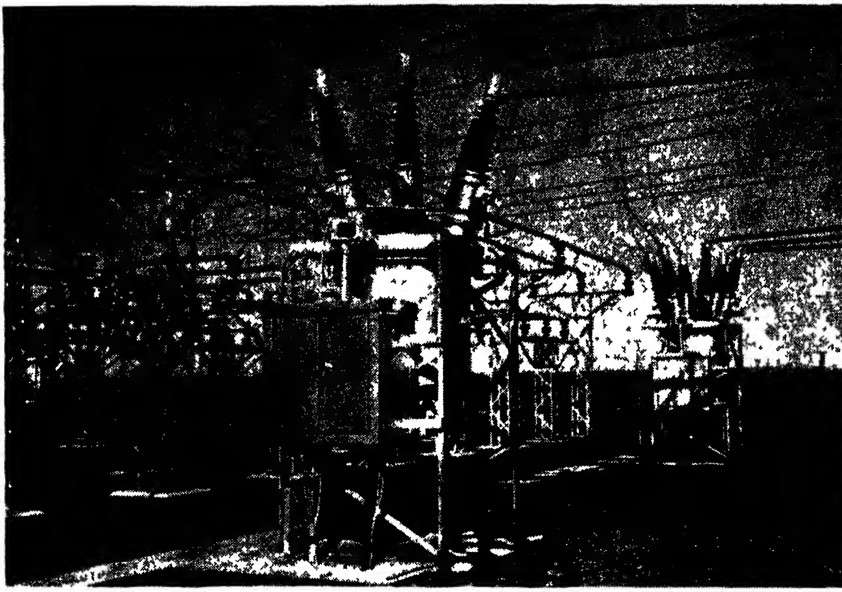


FIG. 6-41.—*66 kV oil circuit-breakers of the single tank type, frame-mounted and seen in a substation of the Kenya Power Company, East Africa (Associated Electrical Industries Ltd.).*

Examples of 132 kV circuit-breakers are shown in Figs 6-42 and 6-43 and it will be seen that separate tanks are used for each phase and that they are floor mounted

Dependent on the rating of the breaker shown typically in Fig. 6-42 each phase may have either two or four breaks. In the four-break arrangement the effective opening speed is doubled leading to short arc-duration with relatively low mechanical speed of the moving contact system. A study of Fig. 6-44 shows that the moving cross-bar carries (at each pole) a moving contact rod and an insulated push rod. In closing, the crossbar travels a considerable distance in oil before the push-rod picks up a hinged contact assembly. The hinged contact is then carried upwards until simultaneous contact is made between the moving, hinged, and fixed contacts. Travel continues beyond this point until the fully closed position is reached. On opening, all four breaks per phase open simultaneously. Elsewhere, we have discussed the reason for resistance elements being connected in shunt across the contacts of an interrupting device and here, in Fig. 6-44, we note an application associated with an oil-circuit-breaker. This method of switching is applied only to certain ratings and for certain system applications. Note too, in Fig. 6-42, the access manholes or ports in the tank sides.

For voltages from 220 kV up to 380 kV, the oil circuit-breaker takes on a different appearance as will be judged from Fig. 6-45.

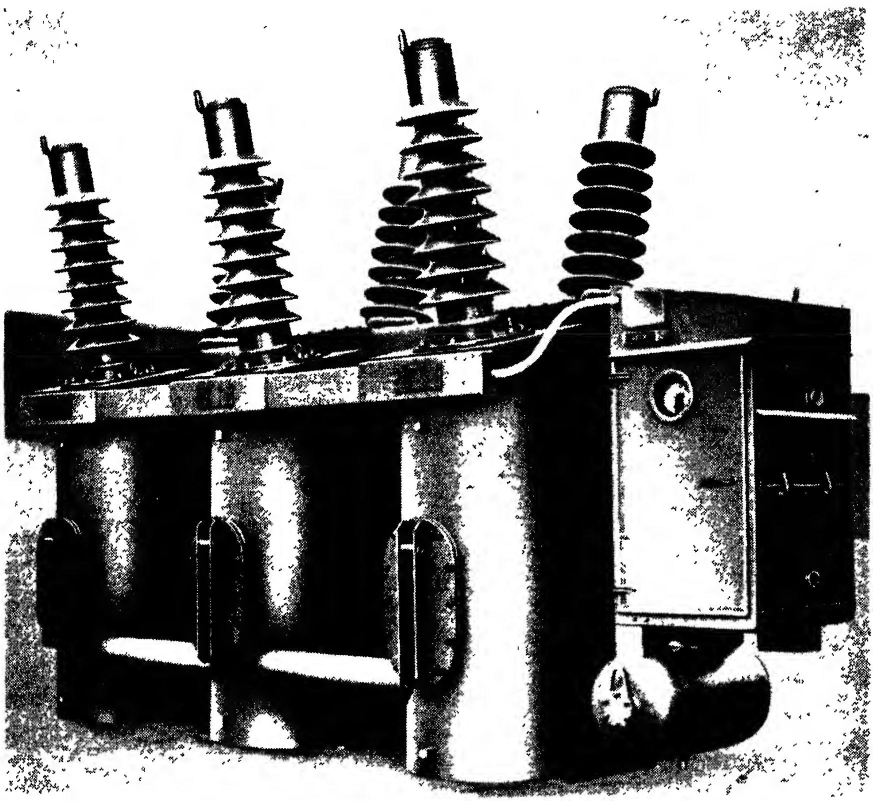


FIG. 6-42.— 132 *kV outdoor oil circuit-breaker with compressed-air closing mechanism (Associated Electrical Industries Ltd.).*

This shows a typical installation of circuit-breakers known by the name "Shuntarc" (Associated Electrical Industries Ltd.) and employing tanks of lenticular shape, each tank, together with the operating mechanism housing, bushing seatings and support structure, being a one-piece steel fabrication.

Dependent on the rating, four or six breaks are employed per pole, the breaks being divided between the two terminals. Fig. 6-46 shows one phase of a four-break breaker with a half-sectional view of the arc-control chambers and switching resistors fitted to one terminal.

A study of the sectionalised view shows that one break in this design (the outer) is of the conventional pattern with the moving contact mounted directly on the crossbar. The other break incorporates a "trapped" moving contact which is normally held in the open position by springs but which is pushed upwards to engage with its fixed contact by an insulation striker rod carried on the crossbar, so that the two breaks which are in series, are

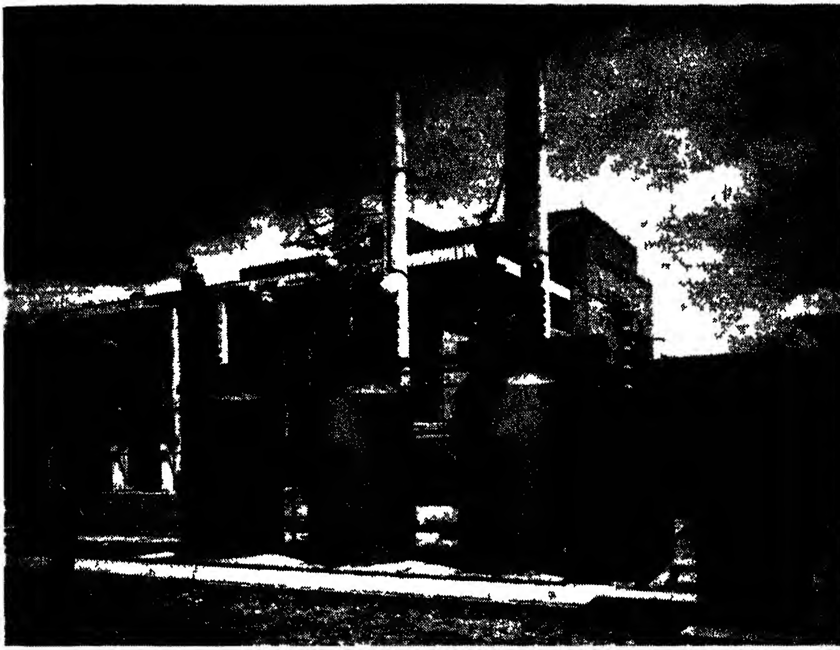


FIG 6-43 —132 *kV outdoor oil circuit-breaker (General Electric Co Ltd)*

operated simultaneously The process of current interruption in such an arrangement showing how the switching resistors are utilised and the resistor current is interrupted, is shown diagrammatically in Fig 6-48

When six breaks per pole are employed, each terminal set of three breaks is mounted across the side of the tank and an ingenious assembly of insulated and current carrying cross-arms is employed to provide a current path as shown in the schematic diagram Fig 6 47

An oil circuit-breaker is defined in B S 116 and B S 936 as "a device capable of making and breaking a circuit in oil under normal conditions and under abnormal conditions such as those of short-circuit" This definition implies that automatic tripping will occur by reason of the operation of associated protective gear It implies, too, that a circuit-breaker must have the ability to interrupt fault currents of specified values applicable to the system and calculated as we have shown in Chapter III There are, however, numerous circumstances where an automatic trip feature is not essential so that the interruption of abnormal current does not arise and such a device then becomes an oil switch In suitable circumstances the employment of an oil switch results in very considerable saving in capital expenditure and in particular it can profitably be employed for ring main switching or as an on-load switching device on the incoming supply to a switchboard comprising a number of oil circuit-breaker units controlling outgoing feeders

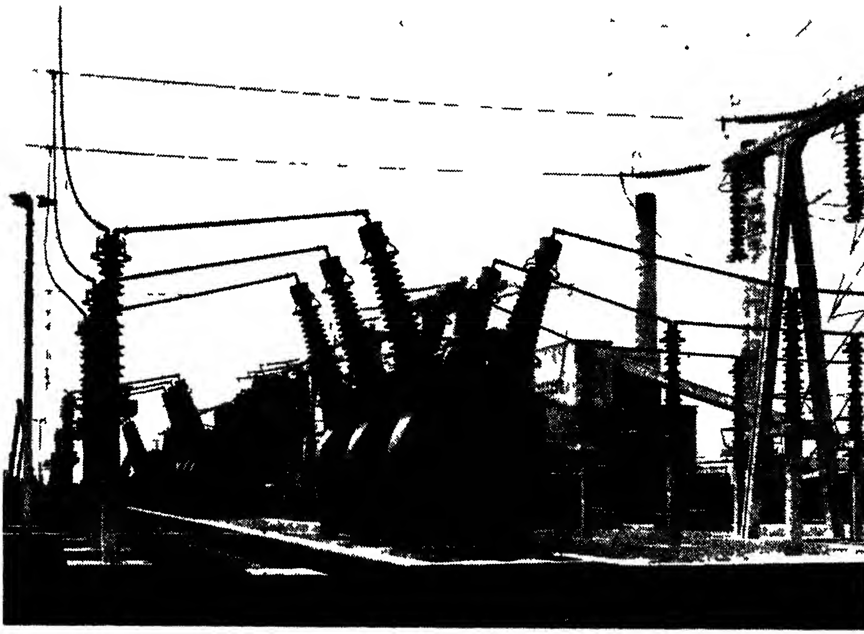


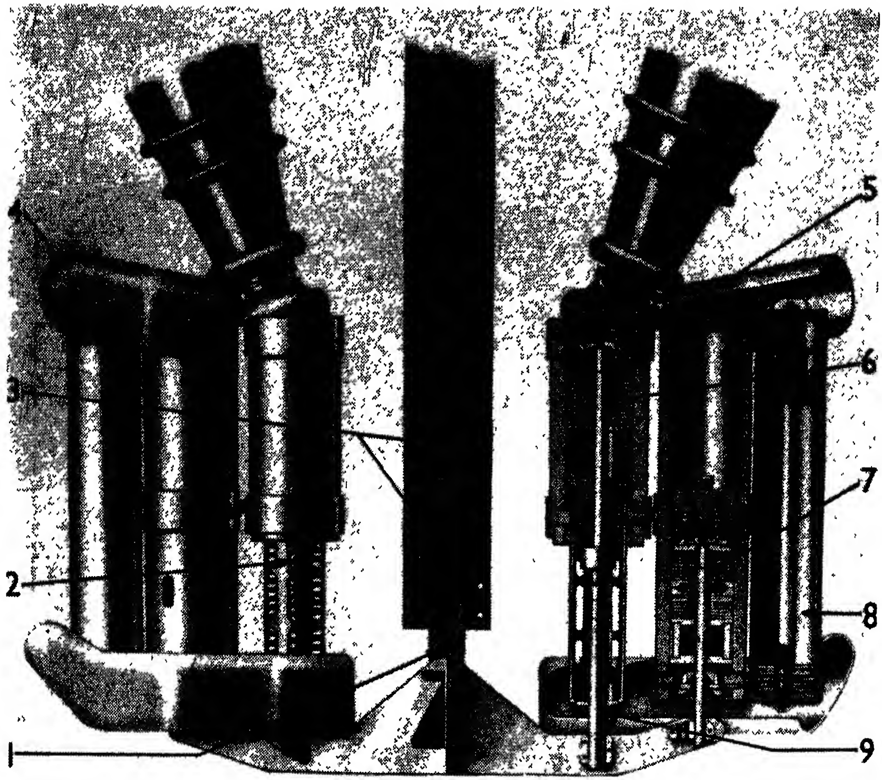
FIG. 6-45.—275 *kV* 7500 *MVA "Shuntarc" outdoor oil circuit-breakers installed at Castle Donnington C.E.G B, East Midland Division (Associated Electrical Industries Ltd.).*

It will be clear that, although not called upon to break fault current, an oil switch may be used to break normal load current, that it may have to carry fault current until the latter is cleared elsewhere and finally, it may be called upon to close on to a fault. These then are the requirements demanded of an oil switch and are those included in B.S. 2631 covering such switches.

This specification covers a range of voltages from 3·3 kV up to 33 kV and at each voltage an upper limit of making capacity of 33 400 amperes (peak) is envisaged and a 3 second short-time rating of 13 100 amperes r.m.s. The normal circuit rating is standardised at 400 amperes and this is the current which the oil switch must be capable of breaking.

Facilities in oil switches designed to B.S. 2631 invariably include integral earthing facilities and means for carrying out tests on the cable connected to the switch. It is necessary that the earthing switch should have the same ability to make on to a fault as the main switch and so, in most designs, both switches are similar in nature, some employing two independent switches with separate but interlocked closing mechanisms and others employing a form of changeover switch with a common hinge point.

The need to be able to close an oil switch on to a fault has resulted in nearly all such switches being fitted with spring-assisted manual closing mechanisms, some features of which we shall discuss in a later chapter.



1 TENSION ROD
2 STRIKER ROD REMOVED TO SHOW SPRING AND TRAPPED MOVING CONTACT IN OPEN POSITION
3 V-GUIDES AND GUIDE BLOCKS
4 UPPER STRESS SHIELD
5 FIXED CONTACTS
6 TRAPPED MOVING CONTACT
7 MOVING CONTACT ROD
8 NON-INDUCTIVE SHUNT RESISTOR
9 INSULATION STRIKER ROD

FIG. 6-46.—*Half-sectional view of arc-control chambers and resistor on one terminal of one phase of a four-break "Shuntarc" circuit-breaker (Associated Electrical Industries Ltd.).*

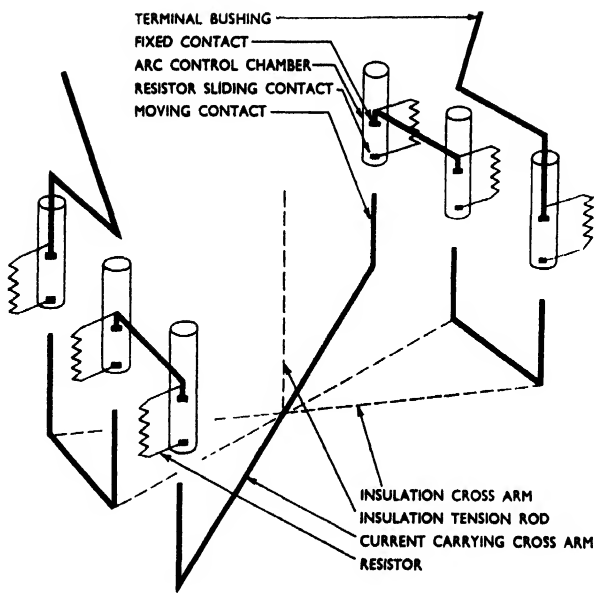


FIG. 6-47.—*Schematic diagram of six-break "Shuntarc" circuit-breaker showing current path (Associated Electrical Industries Ltd.).*

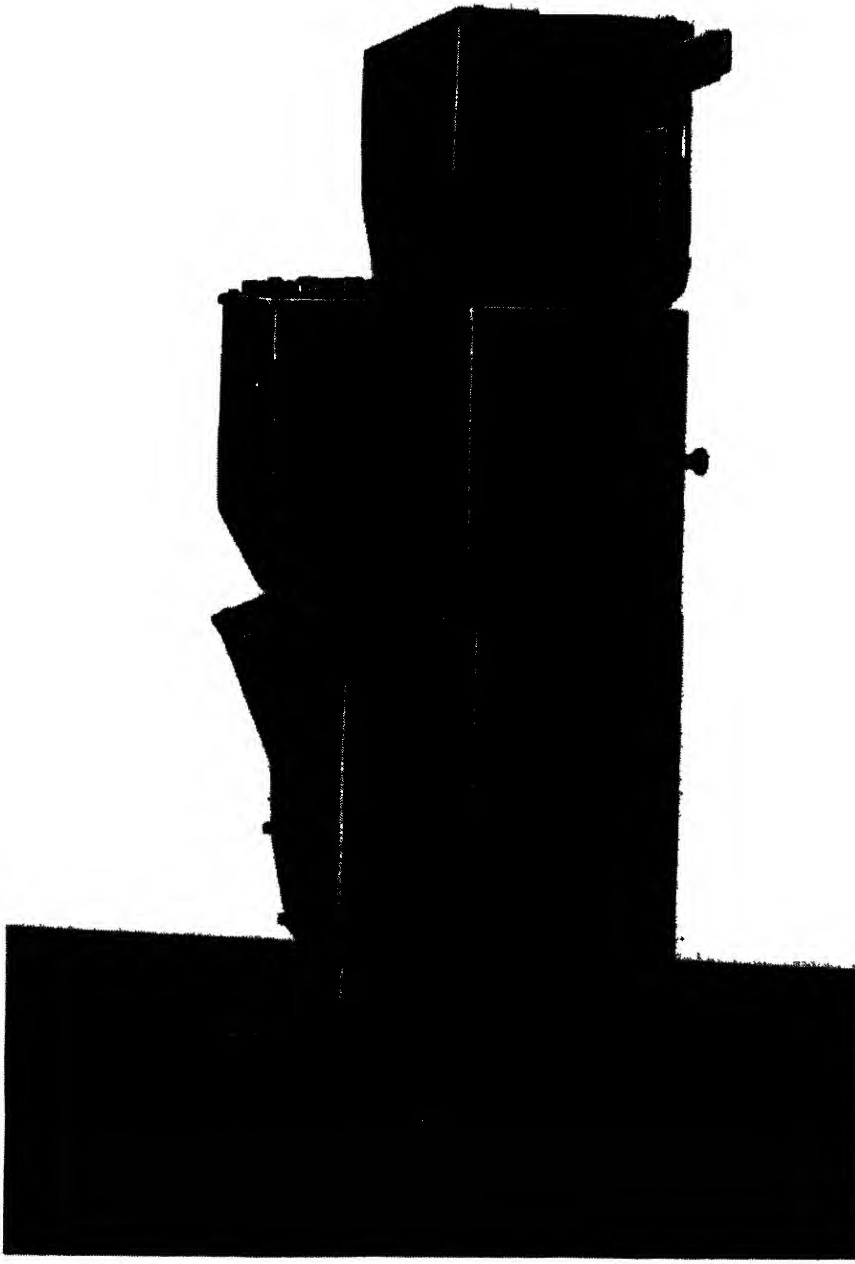


Fig. 6-49.—*Side view of 11 kV oil switch unit with air-insulated busbars (Johnson & Phillips Ltd.)*

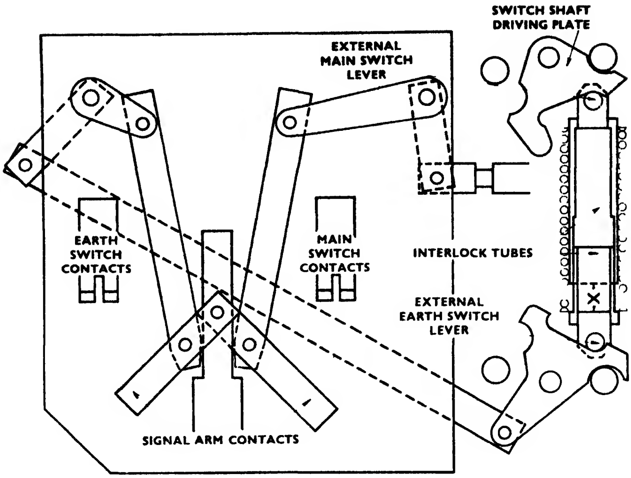


FIG 6-50 —*Showing separate switch blades for "main" and "earth" switching Both switches shown in the "off" position (Johnson & Phillips Ltd)*

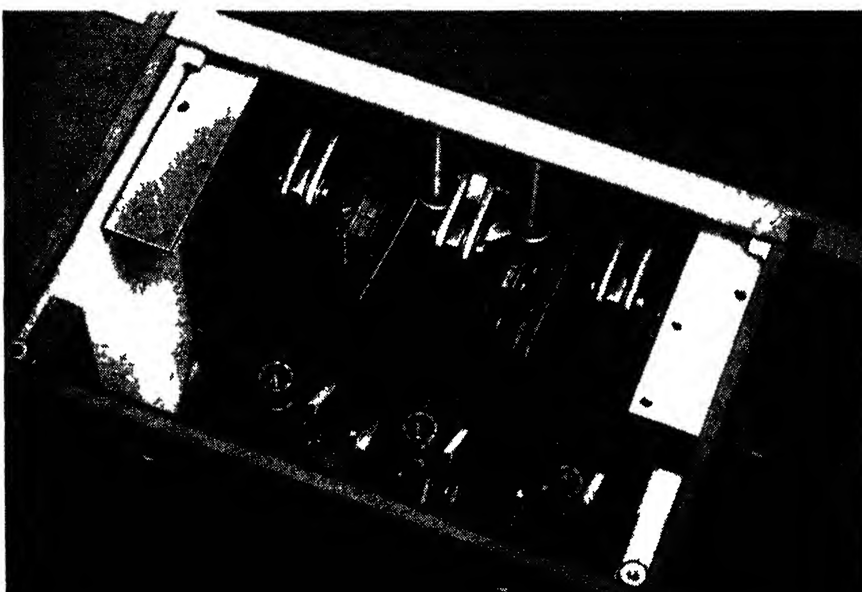


FIG. 6-51.—*Interior view of switch chamber with covers and shutters removed to show cable test orifices (Johnson & Phillips Ltd).*

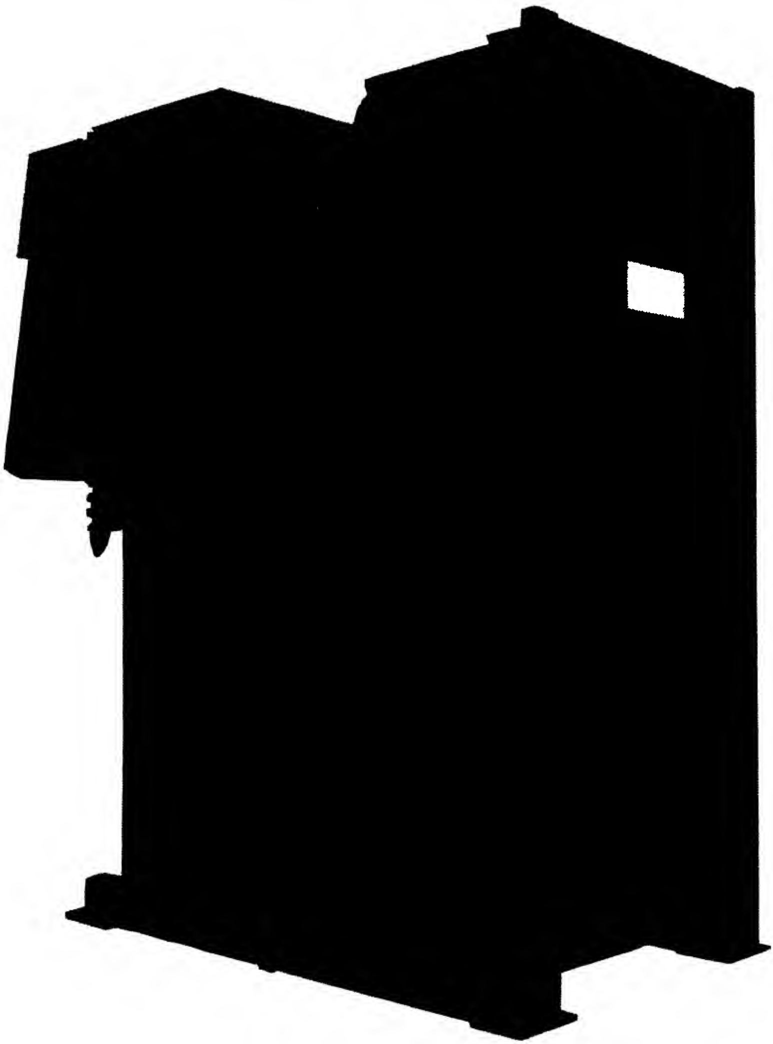


FIG. 6-52.—33 *kV oil switch unit (A. Reyrolle & Co. Ltd.).*

Fig. 6-49 shows (in side view) the appearance of a typical oil switch unit with air-insulated busbars suitable for lining up with oil circuit-breaker units as noted in Chapter X Fig. 10-50. In this design separate switch blades for "main" and "earth" are employed as shown in Fig. 6-50 and each is operated by inserting a lever into either the upper or lower operating spigots. In Fig. 6-51, which illustrates the interior of the switch chamber, can be seen the three test orifices into which cable test plugs may be inserted. Access to these orifices in service is through the top cover but it cannot be obtained until the main switch is off and the earth switch is closed. Having then inserted the test plugs and connected the test leads, the earth switch

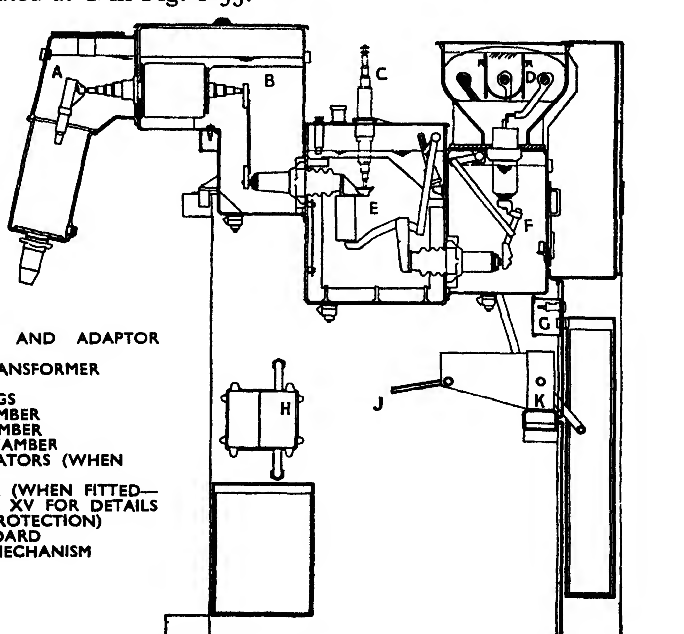
may be opened just prior to applying the test voltage. The action of opening the earth switch automatically traps the test plugs until such time as the switch is reclosed.

An oil switch in which the changeover principle is employed is noted later in Chapter XVIII (Outdoor Switchgear) Fig. 18-23 and here, although using only a single blade, operation from off-to-main or off-to-earth can only be made by inserting an operating lever in an appropriate slot in an escutcheon plate and suitable masking is provided so that only one slot is accessible for the lever at any one position. The unit shown in Fig. 18-23 is effectively an outdoor switch but is available also as an indoor version for lining up with circuit-breakers or other units.

For lining up with their range of vertical-isolation oil circuit-breaker units with compound filled busbars and for 33 kV service, A Reyrolle & Co. have developed an oil switch unit complying with the specification already noted, the unit being shown in Fig. 6-52.

In this design the switching principle employed is different to that we have noted in 11 kV units in that a two-way selector switch is used to make a choice between "service" or "earth" conditions and then, having made this selection, the circuit is completed on a separate oil switch. These switches are noted in Fig. 6-53, at F and E respectively and the mechanisms for operating them are mechanically interlocked to prevent incorrect operation and to ensure that no part of the switching duty falls on the selector switch.

As in designs for lower voltages, facilities for cable testing are provided and are indicated at C in Fig. 6-53.



A — CABLE BOX AND ADAPTOR CHAMBER
B — CURRENT TRANSFORMER CHAMBER
C — TEST BUSHINGS
D — BUSBAR CHAMBER
E — SWITCH CHAMBER
F — SELECTOR CHAMBER
G — NEON INDICATORS (WHEN FITTED)
H — SOLKOR BOX (WHEN FITTED—SEE CHAPTER XV FOR DETAILS OF SOLKOR PROTECTION)
J — FRAME STANDARD
K — OPERATING MECHANISM

FIG. 6-53.—*Cross-sectional view of 33 kV oil switch unit with compound-filled busbars (A. Reyrolle & Co. Ltd.).*

BIBLIOGRAPHY

B.S. 116—Oil Circuit-Breakers for Alternating Current Systems.

B.S. 936—Oil Circuit-Breakers for Medium Voltage A.C. Systems.

B.S. 1086—Code of Practice on the Maintenance of Electrical Switchgear.

B.S. 2631—Oil Switches.

Switchgear Practice, A. Arnold (Chapman & Hall).

Calculation and Design of Electrical Apparatus, W. Wilson (Chapman & Hall).

Elements of Switchgear Design, Dr. Ing Fritz Kesselring (Pitman & Sons).

Electric Power System Control, H. P. Young (Chapman & Hall).

Outdoor High-Voltage Switchgear, R. W. Todd and W. H. Thomson (Pitman & Sons).

Fundamentals of A.C. Circuit Interruption, Dr. Erwin Salzer (Allis Chalmer Mfg. Co., Ltd.).

Switchgear Principles, P. H. G. Crane (Cleaver-Hume Press Ltd.).

Circuit-Breaking, H. Trencham (Butterworth Scientific Publications).

"THE DEVELOPMENT OF THE SINGLE-BREAK OIL CIRCUIT-BREAKER FOR METALCLAD SWITCHGEAR," D. R. Davies and C. H. Flurscheim, "Journal I.E.E.," 1936, Vol. 79.

"ARC CONTROL POTS," C. J. O. Garrard, "General Electric Co. Journal," No. 10, p. 69.

"MECHANICAL INTEGRITY IN THE DESIGN OF ELECTRICAL CIRCUIT-BREAKERS," M. C. Hunter, "Journal I.E.E.," 1940, Vol. 87, p. 665.

"THE MECHANISM OF ALTERNATING-CURRENT CIRCUIT INTERRUPTION," H. Trencham and H. Cox, "Engineering," May 28th, 1937.

"ARC-CONTROL DEVICES," W. A. McNeill and P. H. G. Crane, "Electrical Review," 9th and 16th July, 1954.

"THE PERFORMANCE OF HIGH-VOLTAGE OIL CIRCUIT-BREAKERS INCORPORATING RESISTANCE SWITCHING," H. E. Cox and T. W. Wilcox, "Journal I.E.E.," 1947, Vol. 94, Part II, p. 354.

CHAPTER VII

SMALL-OIL-VOLUME CIRCUIT-BREAKERS

CHAPTER VII

SMALL-OIL-VOLUME CIRCUIT-BREAKERS

In the preceding chapter we have noted the design and special features of what may be described as the bulk-oil type of circuit-breaker for voltages from the lowest up to 380 kV. In the chapter which succeeds this one, we shall note the details of circuit-breakers in which no oil at all is used, i.e. air-blast circuit-breakers, for the voltage range 3·3 kV to 400 kV. When oil is employed, the medium of arc extinction is self-contained, i.e. the oil itself, whereas when no oil is present, outside aid is necessary in the way of compressed air at relatively high pressure.

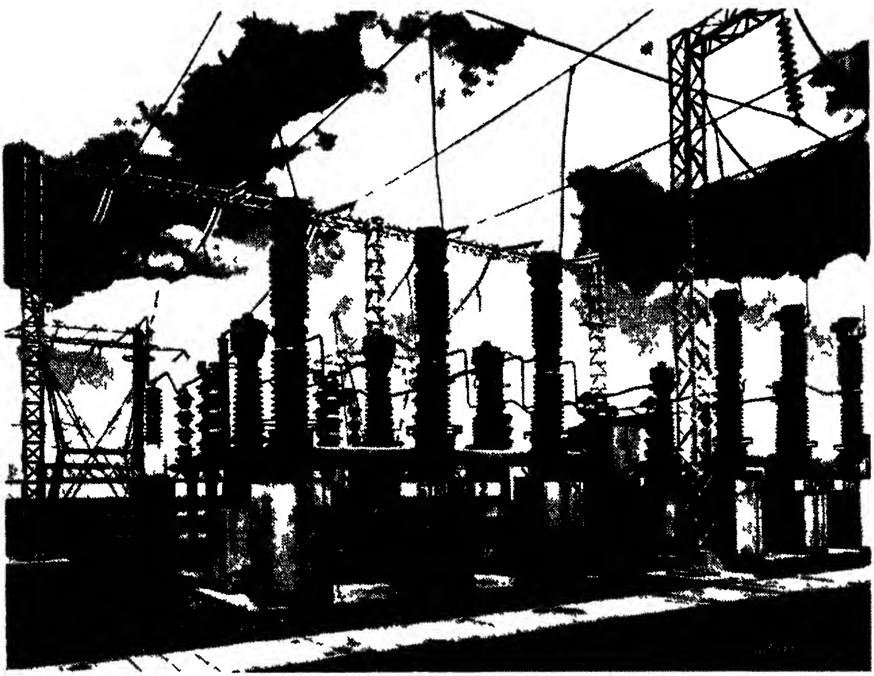


FIG. 7-1.—*Small-oil-volume circuit-breakers in outdoor switching stations (A. Reyrolle & Co. Ltd.).*

Over the years, the oil content in many of the so-called bulk type described in Chapter VI, has been progressively reduced, particularly at the lower end of the voltage range, such reductions arising out of developments in arc control, the use of the single-break design and, in some cases, shaping the tank to conform with the internal structure of the breaker. To this

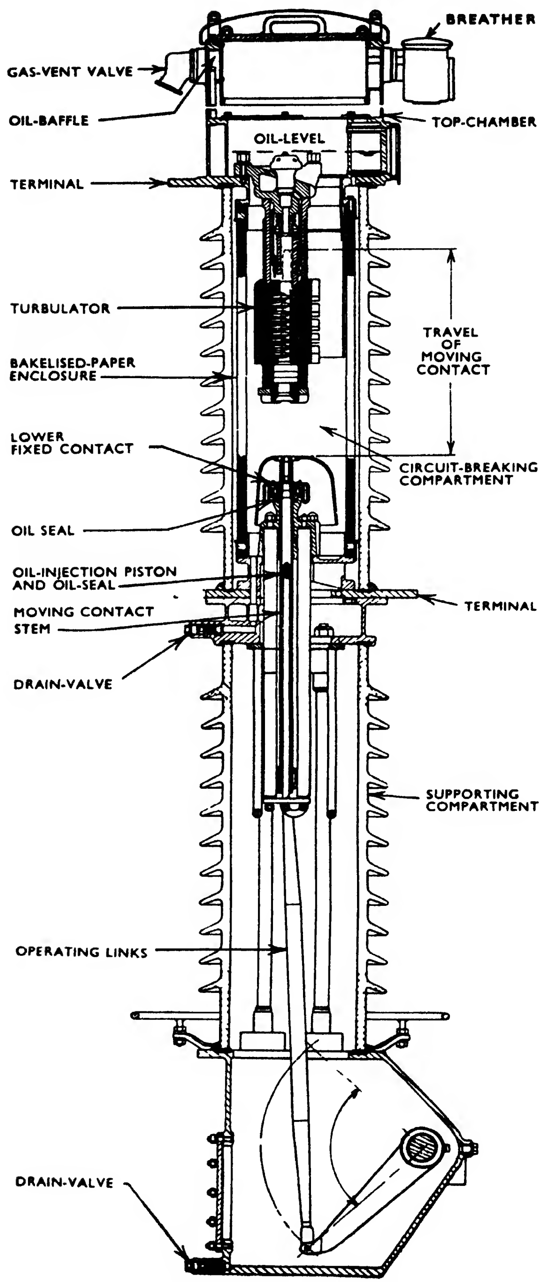


FIG. 7-2.—*Cross-section of one phase of a 132 kV small-oil-volume circuit-breaker (A. Reyrolle & Co. Ltd.).*

extent, Chapter VI may be assumed to cover breakers of relatively small oil volume, but as the voltage increases and in spite of some of these same factors applying, the oil quantity remains high, running at the very highest voltages to some thousand or so gallons for a three phase unit. This is, perhaps, understandable when one remembers the large electrical clearances necessary at the higher voltages.

These large quantities of oil are subject to the carbonisation, sludging, etc., which occurs due to arc interruption and other causes, reducing (in time) the insulating properties and requiring regular maintenance. We have noted also in Chapter VI that when a large circuit-breaker is floor mounted, access to the contact system is not easy and is obtained only through access ports in the tank side after the oil has been pumped away to storage.

It is of interest, therefore, to note here a design which, while retaining oil as the extinguishing media, requires a very much reduced volume of oil and which segregates this oil into two chambers, one for arc interruption and one for insulation, so that the latter is never contaminated by the former. This design is shown in Fig. 7-1 and is available for a voltage range 33 to 220 kV and breaking capacities 1 500 to 7 500 MVA.

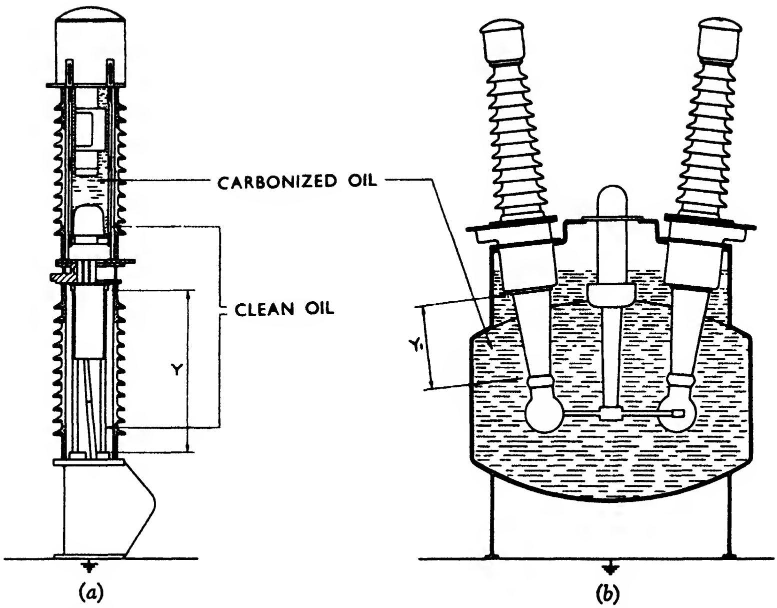
A cross-section of one phase of this circuit-breaker is shown in Fig. 7-2, and a study of this shows clearly the two compartments mentioned, the upper compartment being that in which the arcing process occurs and the lower compartment which supports the upper and provides the main insulation to earth.

Communication between the oil in these two chambers is prevented at the junction of the chambers.

The oil volume in the arcing chamber is, at all voltages, lower than that in the supporting and insulating chamber, so that it is only this smaller quantity which will require maintenance or changing from time to time. The larger volume of oil in the lower chamber, being uncontaminated, ensures a high degree of insulation security in the part of the circuit-breaker which is electrically stressed to earth, irrespective of the condition of the oil in the arcing chamber and whether the circuit-breaker is open or closed. This is demonstrated in Fig. 7-3 which shows a comparison between the stressed paths to earth in a small-oil-volume circuit-breaker and those in a bulk-oil type.

Reverting to Fig. 7-2, it will be seen that the upper arcing chamber comprises a synthetic resin bonded paper cylindrical enclosure within a porcelain insulator. An annular space between these is filled with oil as an insulating medium but, again, this is physically separated from that in the arcing chamber and thus cannot be contaminated.

The circuit-breaker is of the single-break type in which a moving contact tube moves in a vertical line to make or break contact at the upper fixed contacts mounted within the arc-control device. A lower ring of fixed contacts are in permanent contact with the moving arm to provide the other terminal of the phase unit. Within the moving contact tube is a fixed piston, which, as the tube moves downwards on opening, forces the column of oil inside the tube into the arc-control device. This has two effects, firstly, a partial pressure balance is ensured, so that the pressure generated inside the arc-control device has little effect on the acceleration of the



STRESSED PATH TO EARTH SHOWN AT Y (THROUGH CLEAN OIL) AND Y_1 (THROUGH CARBONISED OIL)

FIG. 7-3.—*Comparison of stressed paths to earth in (a) a small-oil-volume circuit-breaker and (b) a bulk oil circuit-breaker (A. Reyrolle & Co. Ltd.).*

moving contact and, secondly, the amount of cavitation caused by the removal of the moving contact is controlled and the efficiency of arc-extinction is increased.

The "turbulator" arc-control device is shown in section in Fig. 7-4, and is built up of oil-impregnated vulcanised fibre plates held under compression by tension members, the plates being arranged to form a series of vents on one side of the arc and a series of oil pockets on the other. The fixed arcing tip is so arranged that when the circuit-breaker opens, the arc is drawn in front of the vents where it can be most easily extinguished. To ensure that oil vaporised by the arc is replaced quickly when the arc is extinguished (this is particularly important for high speed auto-reclosing) a filling valve is fitted in the top casting of the arc-control device.

This valve, lightly spring-loaded, closes when pressure is set up within the device, but as this pressure dies away when the arc is extinguished, the valve opens to allow an inrush of oil.

When a circuit-breaker closes on to a fault there is always a danger that pre-arcing will occur as the moving contact approaches the fixed contacts. In this design this possibility is minimised by fitting inserts of anti-tracking material on the inside edges of the "turbulator" plates.

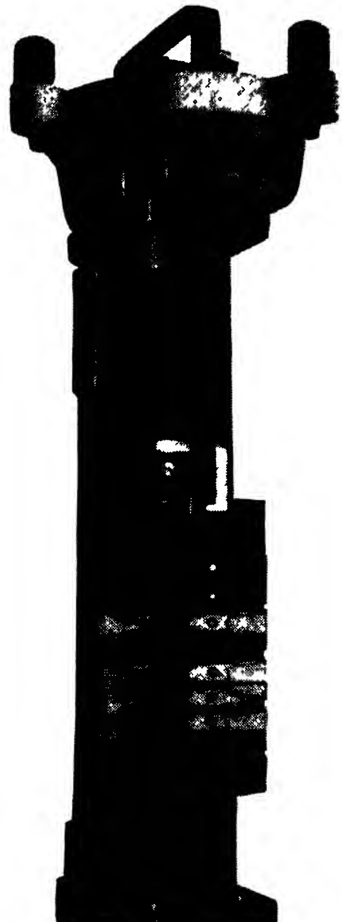


FIG. 7-4.—"*Turbulator" arc-control device used in a small-oil-volume circuit-breaker (A. Reyrolle & Co. Ltd.).*

The upper (arcing) chamber contains a separator which eliminates, by centrifugal action, loss of oil when the breaker operates under fault conditions. It has a spring-loaded vent-valve, a breather to prevent moisture from entering the circuit-breaker, and a safety diaphragm, under the domed cover, designed to lift and protect the circuit-breaker from damage if excessive pressures should arise in the circuit-breaking compartment.

Circuit-breakers of the type described can be used either out-of-doors or indoors, and be mounted either on pedestals or at ground level. At certain voltages and interrupting capacities, two breaks per phase are employed.

We have noted in Chapter VI how in many oil circuit-breaker designs, any necessary current transformers can be accommodated within the breaker, fitted on the bushing insulators. This is not possible in the small-oil-volume type and current transformers must, therefore, be separate units.

These are usually of the post type with low oil-content, the transformer being housed within the porcelain housing and filled with oil under vacuum. Typical current transformers for various voltages are noted in Fig. 7-5.

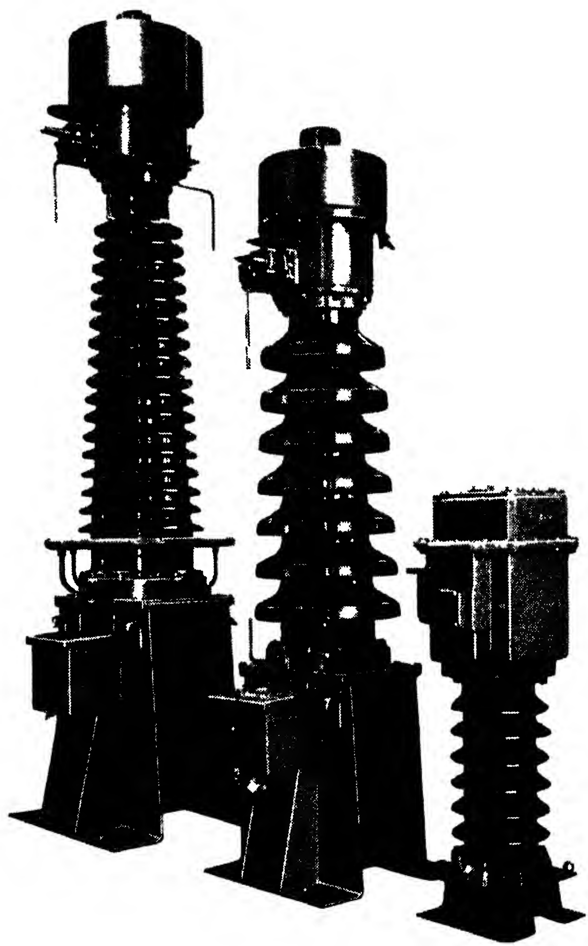


FIG. 7-5.—*Post type current transformers for 220, 132 and 66 kV respectively (A. Reyrolle & Co. Ltd.).*

BIBLIOGRAPHY.

"SAFEGUARDS AGAINST INTERRUPTION OF SUPPLY," H. W. Clothier, B. H. Leeson and H. Leyburn, "Journal I.E.E.", Vol. 82, No. 497, May, 1938.

"PROGRESS IN H.V. METALCLAD SWITCHGEAR," D. R. Davies, "The Metropolitan-Vickers Gazette," April, 1941.

"PROBLEMS AND POSSIBILITIES IN ELECTRICAL SWITCHGEAR," H. Trencham, "B.T-H. Activities," Vol. 15, No. 5.

"THE DEVELOPMENT OF THE SINGLE-BREAK OIL CIRCUIT-BREAKER FOR METALCLAD SWITCHGEAR," D. R. Davies and C. H. Flurscheim, "Journal I.E.E.", 1936, Vol. 79, p. 129.

"CIRCUIT CONTROLLING DEVICES ON POWER SUPPLY SYSTEMS (A REVIEW OF PROGRESS)," C. W. Marshall, "Journal I.E.E.", April, 1942, Vol. 89, Part I, No. 16.

CHAPTER VIII

AIR-BLAST CIRCUIT-BREAKERS

CHAPTER VIII

AIR-BLAST CIRCUIT-BREAKERS

We have noted in Chapter VI the availability of oil circuit-breakers to meet every voltage requirement up to about 400 kV and of varying interrupting capacities up to 7 500 MVA. By continual development such circuit-breakers have met the requirements of many networks, but system voltages and fault levels continue to rise as the demand for electricity rises. For example, the new 400 kV grid system due to start operating in Great Britain in 1965 requires circuit-breakers suitable for a fault level of 35 000 MVA. Future standard voltages will be of the order of 500 kV and 700 kV, noting here a network at 750 kV in the U.S.S.R.

To contemplate the interruption of fault currents up to 50/60 kA at these high voltages in an oil circuit-breaker is probably not impossible, but it would no longer retain any of the simplicity associated with it nor would its performance in many respects match up to the needs of high-voltage networks. It is here that the air-blast circuit-breaker really comes into its own but, as we shall see later, its development has extended down to much lower values of voltage and breaking capacity.

The desirable features to be found in the air-blast circuit-breaker are:—

1. High-speed operation
2. Short arcing times
3. Ability to withstand frequent switching
4. Facility of high-speed reclosure
5. Negligible maintenance.

High-speed operation is very necessary on large interconnected networks in order that system stability can be maintained and in the air-blast circuit-breaker this is achieved because the time interval between the receipt of a tripping impulse (derived from the protective gear applied) and contact separation is very short. Once the contacts part and an arc is drawn it should, ideally, be interrupted in the shortest possible time and this time should be reasonably consistent at all values of current which the circuit-breaker may be called upon to interrupt, i.e. from small line charging or transformer magnetising currents up to the highest value of fault current. This the air-blast circuit-breaker does and arc durations throughout the current range are of the order of one-half to one cycle. In the oil circuit-breaker this consistency rarely exists and because the deionisation processes are largely dependent on the current value, it is usual to find longer arcing times at low current values than at the higher values, and that the whole range of arcing times is higher than in the air-blast design. This aspect is illustrated in Fig. 8-1, noting that the curves shown have no numerical significance in relation to any specific breaker.

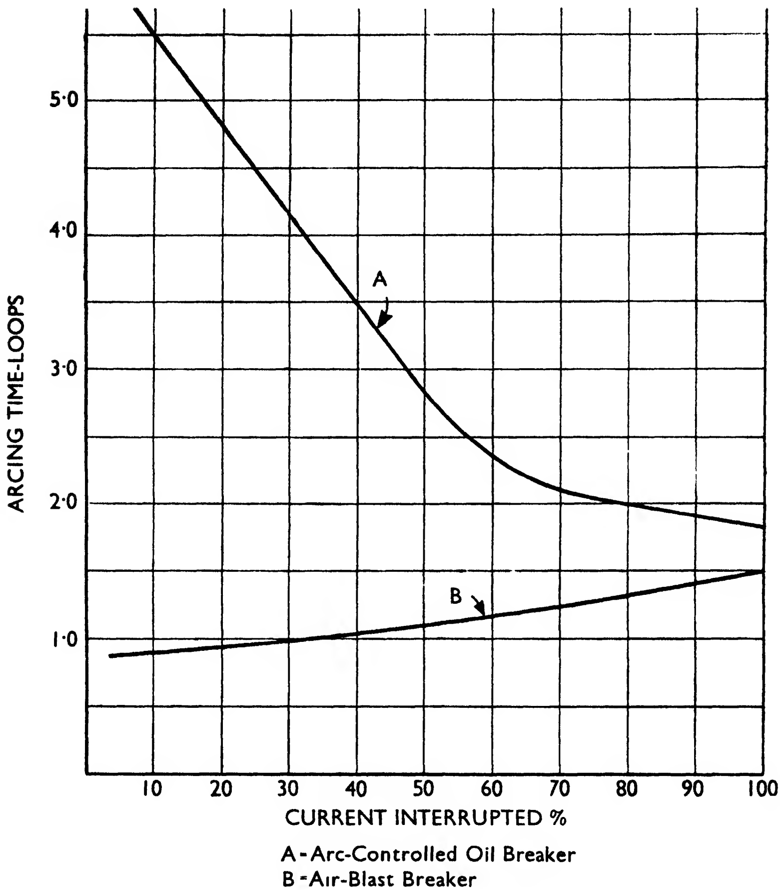


FIG. 8-1.—*Comparison of performance—arcing time/current*

Repeated switching by an air-blast circuit-breaker is possible simply because of the absence of oil, which rapidly carbonises with frequent operation, and because there is an insignificant amount of wear and tear at the current-carrying contact surfaces. At the lower voltages, e.g. 3·3 kV, air-blast circuit-breakers have been most successfully applied to furnace switching, whereas the oil breaker has failed to cope with the necessary switching operations. But it must be remembered that if frequent switching is anticipated, the maintenance of an adequate air supply is essential.

High-speed reclosure by automatic means (single phase or three phase) is an advantage on high-voltage interconnected networks to assist and maintain system stability during the clearance of transient faults, a type of fault which is perhaps in the majority on overhead lines. Provided that the time interval between fault interruption and reclosure is chosen to permit insulation recovery, then a system can often be restored to normal by

breaker reclosure, the cause of the interruption (insulator or line flashover) having disappeared. The low inertia of the moving contacts in air-blast circuit-breakers and the relative ease with which compressed-air mechanisms can be reversed, all help in very short restoration times being achieved.

The ability of the air-blast breaker to cope with repeated switching also means that negligible maintenance is required. For example, the relatively large quantities of oil essential in the oil breaker require an installation of oil filtering plant and very regular treatment of the oil. No such need arises with an air-blast installation.

Against this formidable array of advantages, however, it must be pointed out that compressed-air at the correct pressure, clean and dry, must be available at all times, involving in the largest installations a plant of no mean dimensions, with two or more compressors and an extensive air supply network in the form of a ring main or duplicate bus system. The maintenance of this plant and the problem of air leakages at the pipe fittings are factors which operate against air-blast circuit-breakers in many (smaller) installations and it is a costly adjunct for lower voltage systems as compared with the use of oil or air-break circuit-breakers.

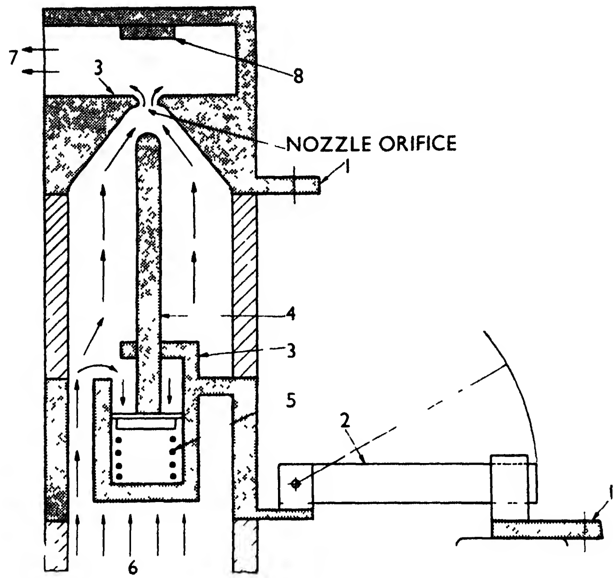
Because the air-pressure is fixed, it is obvious that this will be available regardless of the magnitude of current the breaker is being called upon to interrupt. It must, naturally, be sufficient to deal with the highest value of current to be expected, but this means that it can be very drastic in its effect on small currents and the problem of current chopping arises leading to serious over-voltages, as we have noted in Chapter II.

In that chapter also, note has been made of sensitivity of the air-blast circuit-breaker to circuit severity, i.e. the rate of rise of restriking voltage. Many air-blast circuit-breakers (and some very high-voltage oil circuit-breakers) overcome this problem by resort to resistance switching wherein external resistances are automatically connected in shunt with the contact gap and thereby damp out any high restriking voltage transients caused by current chopping. How these resistances are employed has been shown in simple terms in Fig. 2-6.

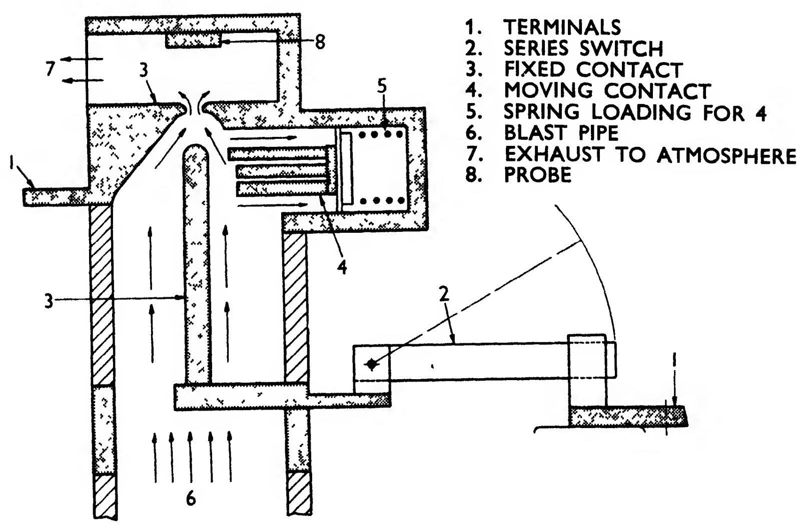
As we shall see later, many air-blast circuit-breakers for the higher voltages employ a number of interrupter heads per phase, each taking a share in the interrupting duty and whether this share is equal in all heads depends largely on the voltage distribution across them. The shunt resistors noted play some part in this voltage equalisation coupled, in some designs, with capacitance also connected across the interrupter heads.

Much of the discussion to this point has been based on the assumption that the circuit-breaker is of the type in which the flow of air is axial, i.e. the stream of air is in line with the arc. There are several forms of this type, the two in most frequent use being those shown in Fig. 8-2.

In both forms, the moving contact is opened by the pressure of air admitted to the interrupter head when a tripping impulse leads to the opening of the blast valve. Movement of the contact will be seen to be limited to give a critical gap for arc extinction and is probably not more than about 0·75 inch. This is shown by the shaded area in Fig. 8-3 and at (a) is shown the need for the critical gap to be reached quickly if the current is to be interrupted at the first or second current zero (curve 1) as compared with the condition (curve 2) where arcing may persist for 3 and 4 cycles.



(a) AXIAL BLAST WITH VERTICAL MOVING CONTACT



(b) AXIAL BLAST WITH SIDE MOVING CONTACT

FIG. 8-2—*Principle of axial blast interrupters (schematic only)*

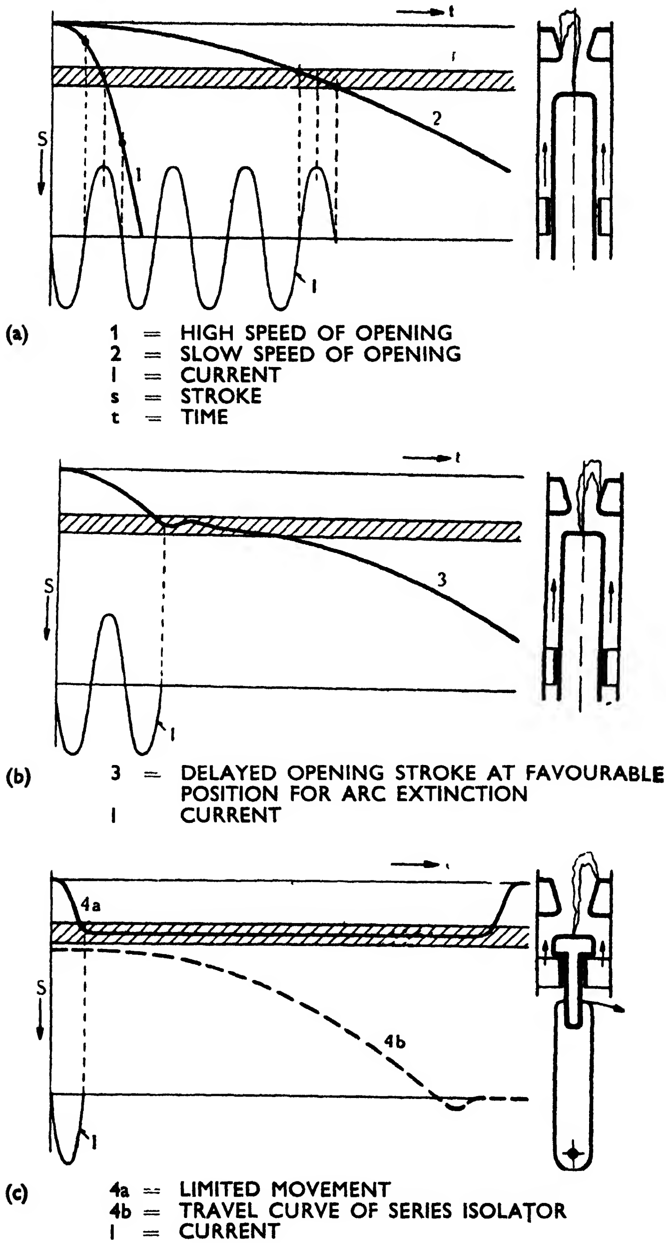


FIG. 8-3.—*Illustrating the interruption of an arc in a critical gap.* (*Messrs. Brown-Boveri & Co., Ltd.*).

At (c) in this illustration is shown the condition where the moving contact reaches the critical gap at high speed, stays at this point until the air supply is cut-off and then recloses. It will be clear that if the moving contact is limited to give a gap of, say, 0·75 inches, such a gap will be insufficient for circuit isolation and it becomes necessary to employ the series isolating switch shown in Fig. 8-2. The opening of this switch is automatic in that after a time interval sufficient for arc extinction in the interrupter head, compressed air is admitted to a piston to cause the series switch to open and, during its travel, cut off the air supply to the interrupter head.

As the air pressure here falls, the moving contact returns under spring pressure to the closed position, as shown in the curve 4a, Fig. 8-3. The dotted curve 4b in this illustration represents the travel curve of the series switch.

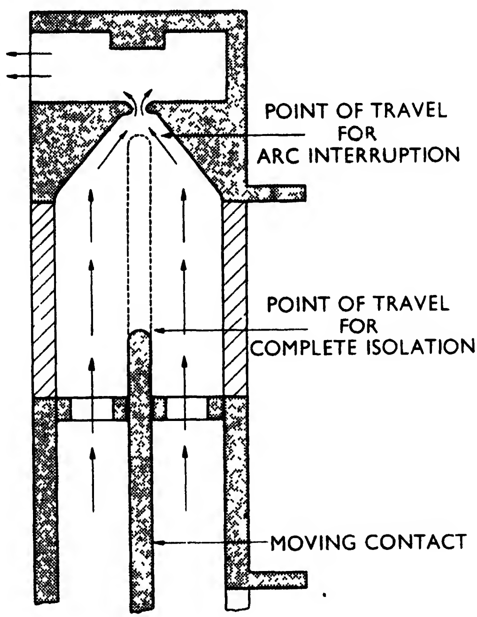


FIG. 8-4.—*Showing extended travel of moving contact for system isolation. (Schematic only) see also Fig.* 8-3 (*b*).

Reclosure on an air-blast circuit-breaker is, under these conditions, a function of the series switch as the circuit-breaker moving contact is already closed. To close the series switch, air is admitted to a closing piston and the operation is one demanding high speed as, if needs be, the series switch must perform the onerous duty of making on to a fault, a duty we have already discussed in Chapter V.

It is not absolutely essential that an axial flow air-blast circuit-breaker should have a series isolator as it is possible to arrange that after arc

extinction the moving contact is allowed to continue its travel to a position where the gap is ample for circuit isolation at system voltage. The principle of this is shown in Fig. 8-4 and, to be most effective, the moving contact should be delayed in its movement for a short time at the critical gap. This feature is shown in Fig. 8-3(b) by curve 3, but its practical application is not very simple.

Air admitted to the interrupting head is usually at a pressure between 200 to 300 lbs. per sq. in., but it has been reduced to this figure at reducing valves from a storage pressure approximately twice as high. In the contact breaking area, the air has to flow through a narrow orifice and beyond this is exhausted to atmosphere carrying with it the hot gases and products of arcing. On reaching atmospheric pressure at what is known as the "down-stream" end of the interrupter head, considerable expansion occurs such that the velocity of the air flowing in the orifice is extremely high, drawing the arc with it into the orifice and concentrating it into a small diameter. At current zero the air-blast is very effective as the arc column is very narrow and, on interruption, the dielectric strength recovers rapidly.

An interesting comparison between air-blast and oil circuit-breaker performance may be noted here. It is that in the oil circuit-breaker, if the arc is not interrupted at the first current zero after the contacts have parted, interruption at the next current zero has an improved chance because the arc length and the gas pressure have both increased, but in an axial-blast air-blast design, the arc length cannot be increased beyond the limited movement of the retracting contact (its full movement is reached in an extremely short time) and further, pressure of the air may fall. For this reason an ample factor of safety in the air reservoir pressure must be allowed.

At the higher voltages, two or more interrupter heads are used in series per pole to provide a multi-break arrangement and if a unit interrupter is developed the number required for a particular voltage rating may be determined by the performance of the unit. This means too, that, subject to control of the restriking and recovery voltages by resistors and/or capacitors as previously described to ensure equal distribution and provided that the air distribution system is symmetrical to each head, the breaking capacity will be shared equally by all the heads of any one phase. This is an important feature in short-circuit testing because no short-circuit test plant capable of affording full-scale testing facilities for values of MVA running into five figures could possibly be economically justified. In an article* reviewing air-blast circuit-breakers for very high voltages, Simpson has given the table reproduced below showing typical ratings of multi-break breakers for four, six, eight and ten breaks over a range of voltages.

No. of breaks per pole	MVA at			
	150 kV	220 kV	275 kV	380 kV
4	7 500	7 500	—	—
6	—	10 000	10 000	—
8	—	—	15 000	15 000
10	—	—	—	20 000

* *Journal I.E.E. Vol. 4. Number 41, May 1958, p 233*

Similarly, Flurscheim, in an article published in 1954, has given a set of curves illustrating the interrupting performance of a three phase air-blast circuit-breaker with four, eight and twelve interrupting heads per phase, the curves being reproduced in Fig. 8-5.

Before proceeding to show some examples of typical air-blast circuit-breakers of the type described, it is worth noting that there is another type, but with a much more limited application, probably 11 kV and about 750 MVA. It is the type known as "cross-blast" and as far as is known to the author, there is no example of the type currently in production in Great Britain.

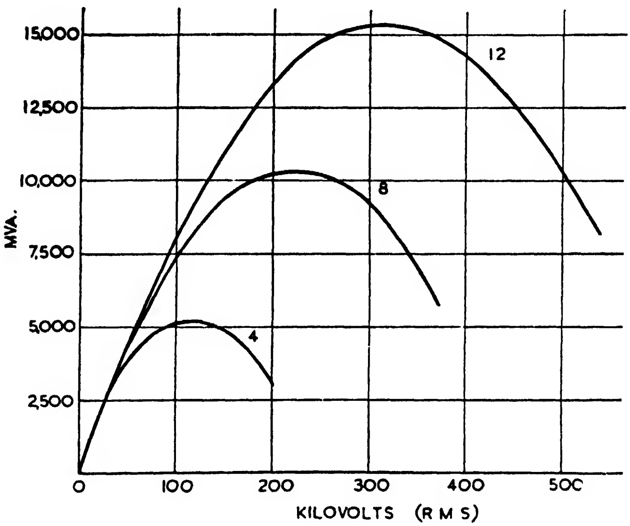


FIG. 8-5.—*Typical interrupting performance of three phase air-blast circuit-breakers with 4, 8 and 12 single-flow interrupters per pole ("The Engineering Journal", Canada, Dec. 1953, and "The MV Gazette", July 1954.)*

The principle employed in the cross-blast design is fundamentally different from the axial-blast and, as seen in Figs. 8-6 and 8-7, the moving contact arm operates in close proximity to an arc chute to draw an arc which is forced by a transverse blast of air into the splitter plates within the arc chute, thereby lengthening it to the point when it cannot restrike after current zero. The consistent high-speed operation of the axial-blast type is not reproduced in this type, but as the air blast is constant regardless of current value, it is quite efficient in switching small currents. Because the moving arm is not restricted (relatively) in its travel, full isolation is obtained without the need for a series isolator as in other types.

Resistance switching is not normally required as the lengthening arc automatically introduces some resistance to control the restriking voltage transient, but if extra resistance is thought desirable, it is possible to introduce this by connecting it in sections across the arc splitters.

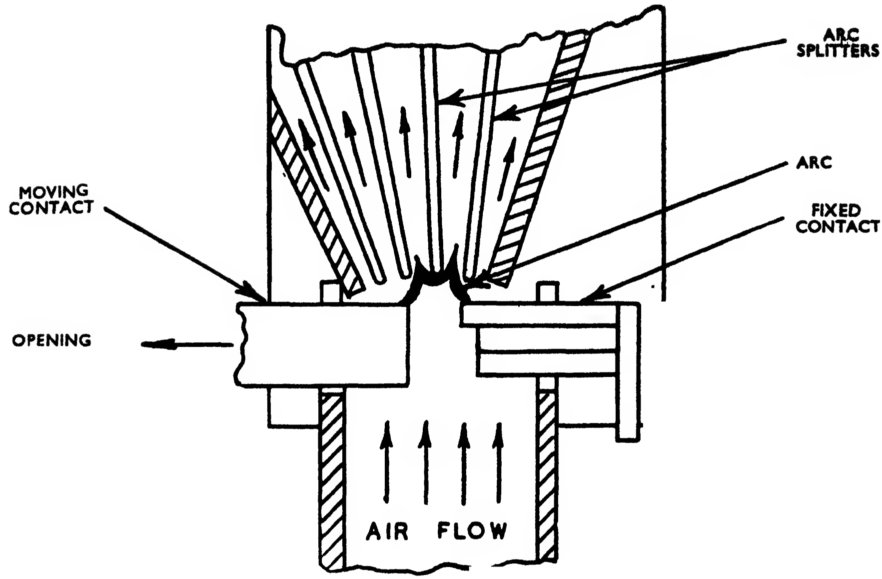


FIG. 8-6.—*Principle of cross-blast air-blast circuit-breaker.*

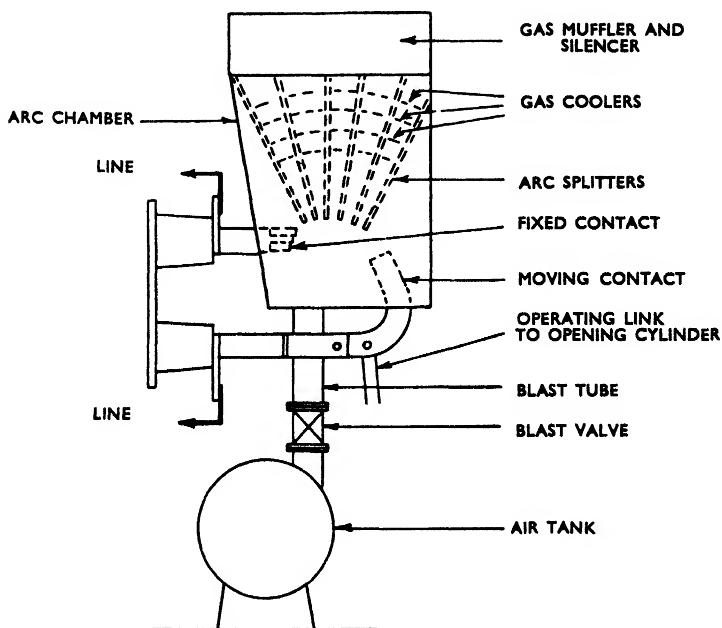


FIG. 8-7.—*Outline of cross-blast air-blast circuit-breaker.*

It is now possible to take note of some actual air-blast circuit-breakers and first refer to a range made by Associated Electrical Industries Ltd, covering the voltage range 66–330 kV and with breaking capacities from 1 500 to 10 000 MVA This range, a typical example of which is shown in Fig 8-8, employs interrupter heads operating on the principles described for axial flow

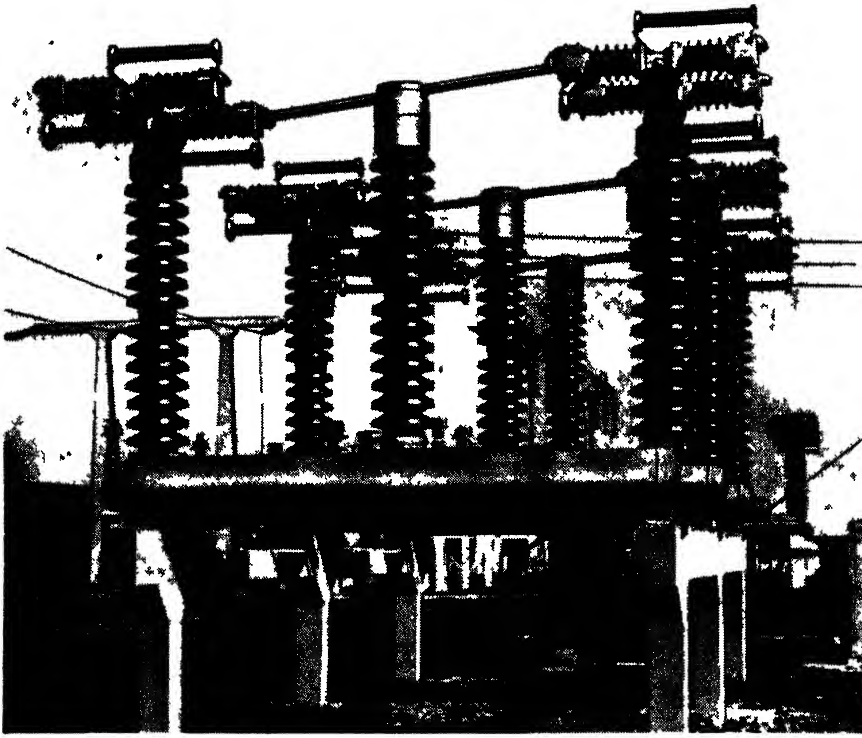


Fig 8-8 —*275 kV air-blast circuit-breaker installed at Carrington Power Station with eight interrupting heads per phase (Associated Electrical Industries Ltd)*

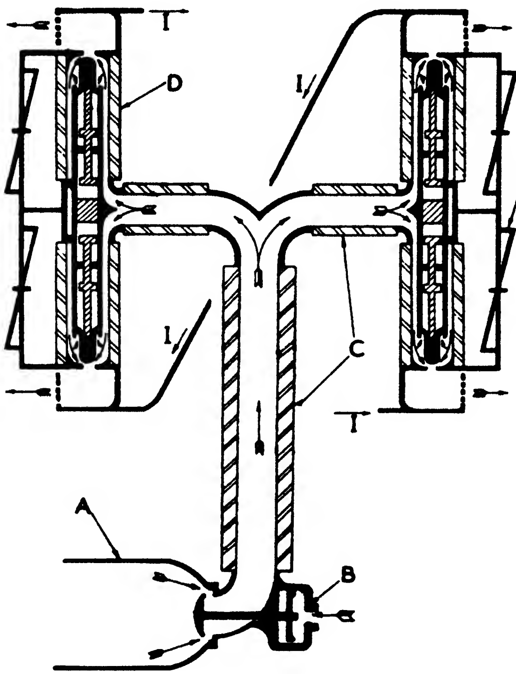
Note from this illustration how the blast columns below the interrupter heads and the centre post carrying the series switch are mounted directly on an air receiver (one per phase) which stores air locally from a main storage located elsewhere

Fig 8-9 shows, diagrammatically, the arc-interrupting process in an interrupter head

In studying Fig 8-9, it should be noted that the central air feed pipe branches to feed the interrupter head shown to the left and a second head (not shown) to the right and identical in every way, the two being in series electrically How a number of heads are assembled in a multi-break

arrangement will be clear from Fig. 8-10, which shows four interrupting heads in series and which in turn are in series with another identical group to form a single-pole unit having eight breaks as shown in the bird's-eye view in Fig. 8-11.

In the general technical discussion earlier, mention has been made of the series switch which must be used to finally isolate the circuit after arc



A—AIR RESERVOIR
B—BLAST VALVE AT EARTH POTENTIAL
C—PORCELAIN BLAST TUBES
D—PORCELAIN INTERRUPTING CHAMBER
E—NON-LINEAR RESISTOR

FIG. 8-10.—*Schematic arrangement of four interrupting elements with identical synchronised air supplies (Associated Electrical Industries Ltd.).*

interruption. This switch is seen in the closed position carried by the centre post insulator, the blade, when operated by its driving system, rotating to take up a position at right angles to the centre line of the interrupter heads.

Fig. 8-10 shows how symmetry is obtained in the air supply to a group of four interrupting heads which, as pointed out earlier, is essential to ensure that each head interrupts its equal share of the total current.

The majority of air-blast circuit-breakers will be installed out-of-doors and be subject to every weather condition under extremes of temperature. The series switch will be particularly affected in these circumstances when subject to severe icing conditions and it is important that whatever happens

the switch must be able to break away and subsequently to re-make. To this end tests are carried out and Fig. 8-12 (upper picture) shows a test condition applied to the series switch with the blade in the closed position and with ice surrounding the contacts to a considerable thickness, a condition maintained for several hours prior to opening the switch as shown in the lower picture.

In the majority of high-voltage oil-break circuit-breakers it is possible to incorporate ring-type current transformers over the bushings but in many air-blast designs no such bushing is available and in this event the necessary transformers must be separately mounted. As we shall see later, the current transformer can, in some designs, be incorporated in the post insulator carrying the fixed contact for the series switch.

Typical of the separately mounted current transformer is that shown in Fig. 8-13.

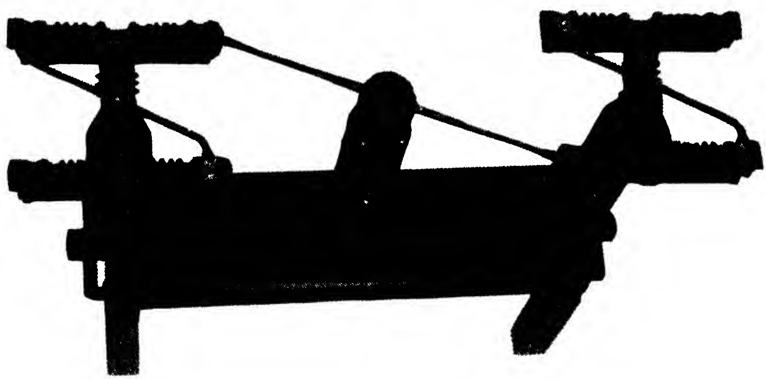


FIG. 8-11—*View from above showing a single pole 275 kV unit with eight breaks per pole (Associated Electrical Industries Ltd.).*

This is an oil-filled unit with an oil-sealing chamber above the primary terminal chamber. This sealing chamber is divided by a vertical partition, an aperture at the base of which permits oil to flow from one half of the chamber to the other. The space above the oil in one half of the chamber is vented to the outer atmosphere while the space above the oil in the other half communicates through a pipe with the space above the main body of oil in the primary terminal chamber, the spaces being filled with nitrogen. Thus, the main body of oil is not in contact with the outside atmosphere but is free to expand without significant change in pressure.

In a range of designs manufactured by The English Electric Co. Ltd., for voltages 3·3 to 66 kV, the air-blast circuit-breakers are suitable for indoor accommodation in cubicles, cells, or blockhouses, the short-circuit ratings extending from 250 MVA at 3·3 kV up to 2 500 MVA at 65 kV. For voltages higher than this the designs are for outdoor use and extend up to 650 kV (projected) with a range of interrupting capacities up to 50/60 kA.

FIG. 8-12—*Showing severe icing test on the series switch of an air-blast circuit-breaker (Associated Electrical Industries Ltd.)*

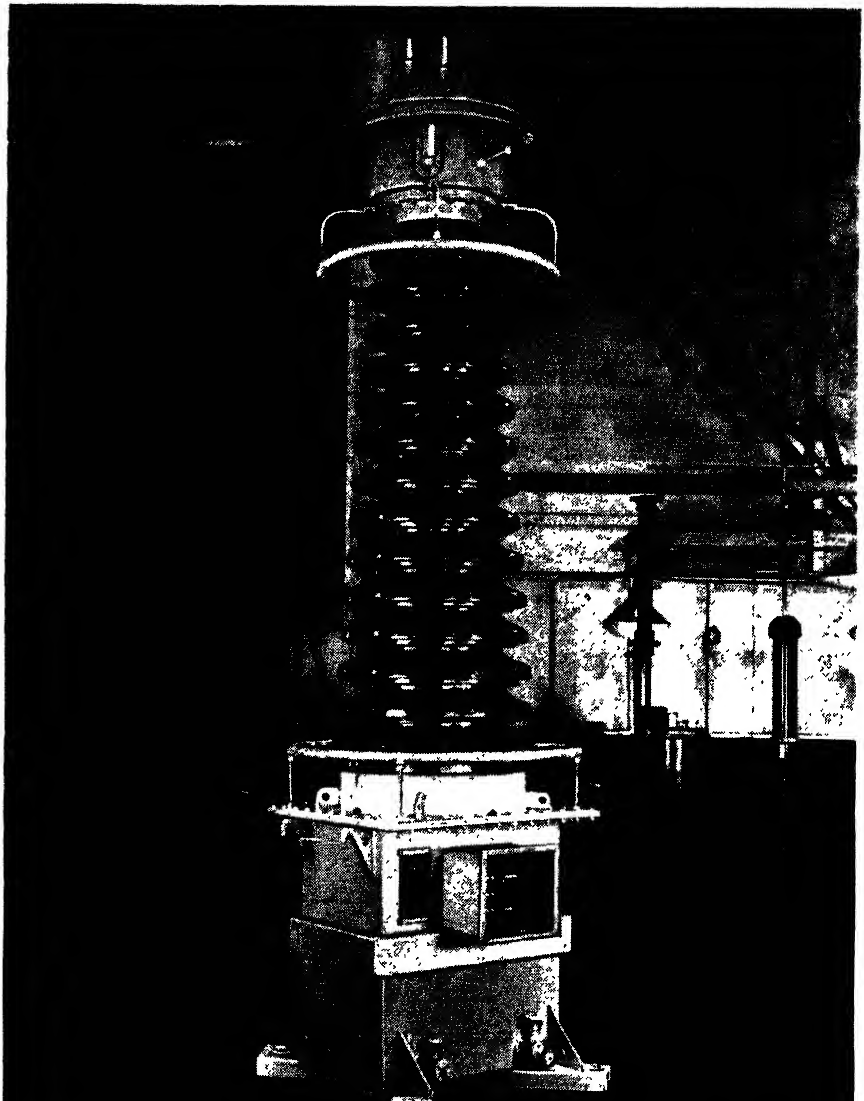


FIG. 8-13. –*Outdoor current transformer for service voltages 220/275 kV (Associated Electrical Industries Ltd.).*

Up to 33 kV a single vertically-mounted interrupter head is employed operating on the axial-blast principle previously described, employing a series switch for final isolation and on closing, to "make" the circuit (the illustrations following describe this switch as a "make switch"). At voltages from 3·3 to 11 kV, the circuit-breakers are available with normal current ratings up to 3 000 amperes and as currents of such magnitude cannot be carried within the interrupter head, a by-pass switch is employed to carry this main current but so arranged that it has no duty in fault interruption. This involves an air-operated mechanism which, when a breaker tripping impulse is received, causes the by-pass switch to open *first* and in so doing initiates the opening of the valve system to admit air to the interrupter head, open the interrupter contacts and finally open the series switch. When reclosing the breaker, the procedure is reversed so that the by-pass switch closes last With this arrangement, the by-pass switch is external and has no ability to break or make current. As noted earlier, the range of air-blast circuit-breakers for the lower voltages is essentially for

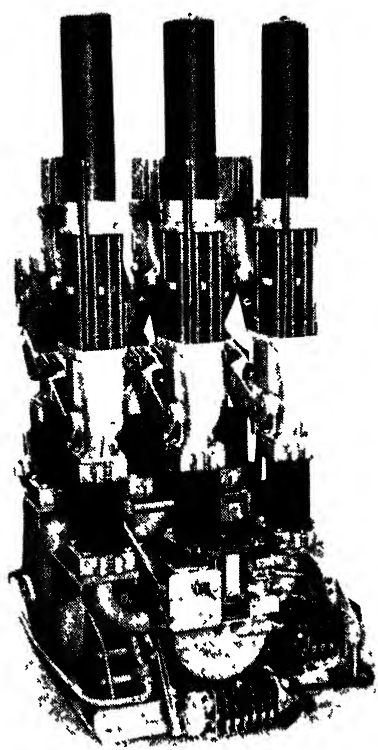


FIG. 8-14.--*Indoor type air-blast circuit-breaker with by-pass switch for heavy normal current ratings 3·3/11 kV. Frame "h" (English Electric Co. Ltd.).*

indoor accommodation and Figs 8-14, 8-15, 8 16 and 8-17 serve to illustrate the range to 33 kV

In the 66 kV indoor type, two interrupter heads in series are used per pole and are located in a horizontal insulator, each head having its own cooler and blast valve As seen in Fig 8-18, there are two air receivers per three phase circuit breaker

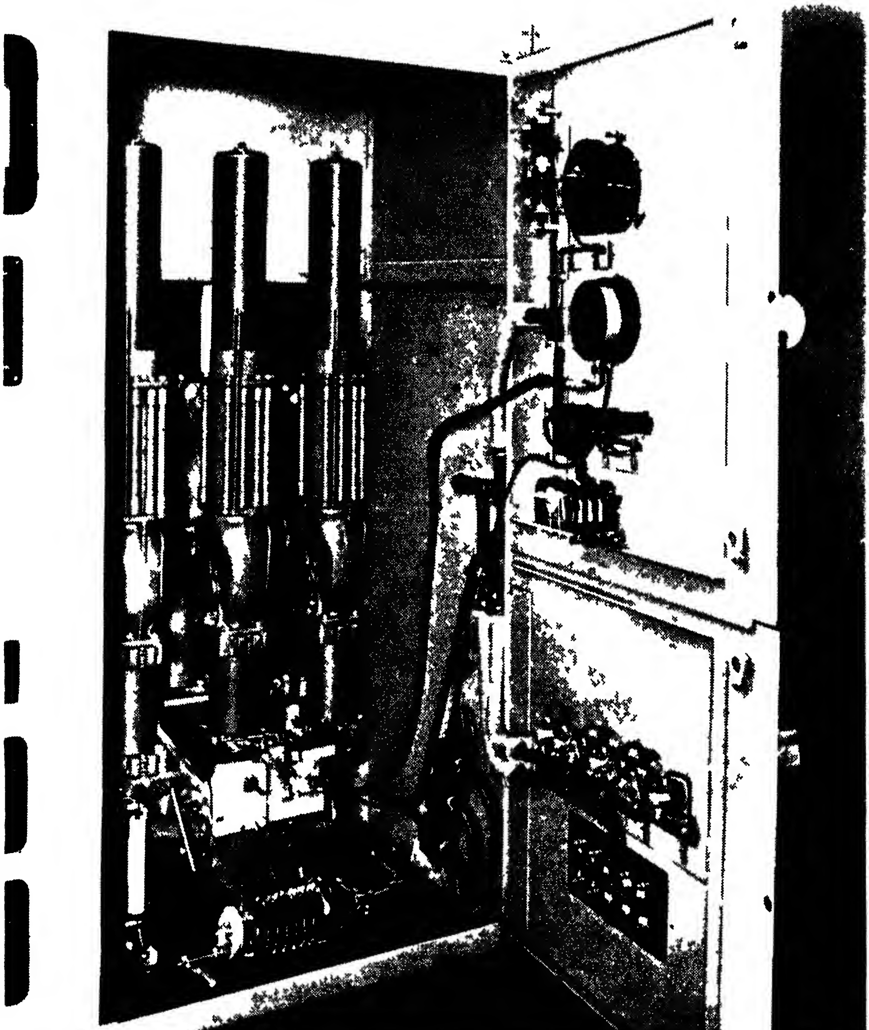


FIG 8-15 *Air blast circuit-breaker 11 kV as Fig 8 14, mounted in sheet steel cubicle doors opened and h v guard removed (English Electric Co Ltd)*

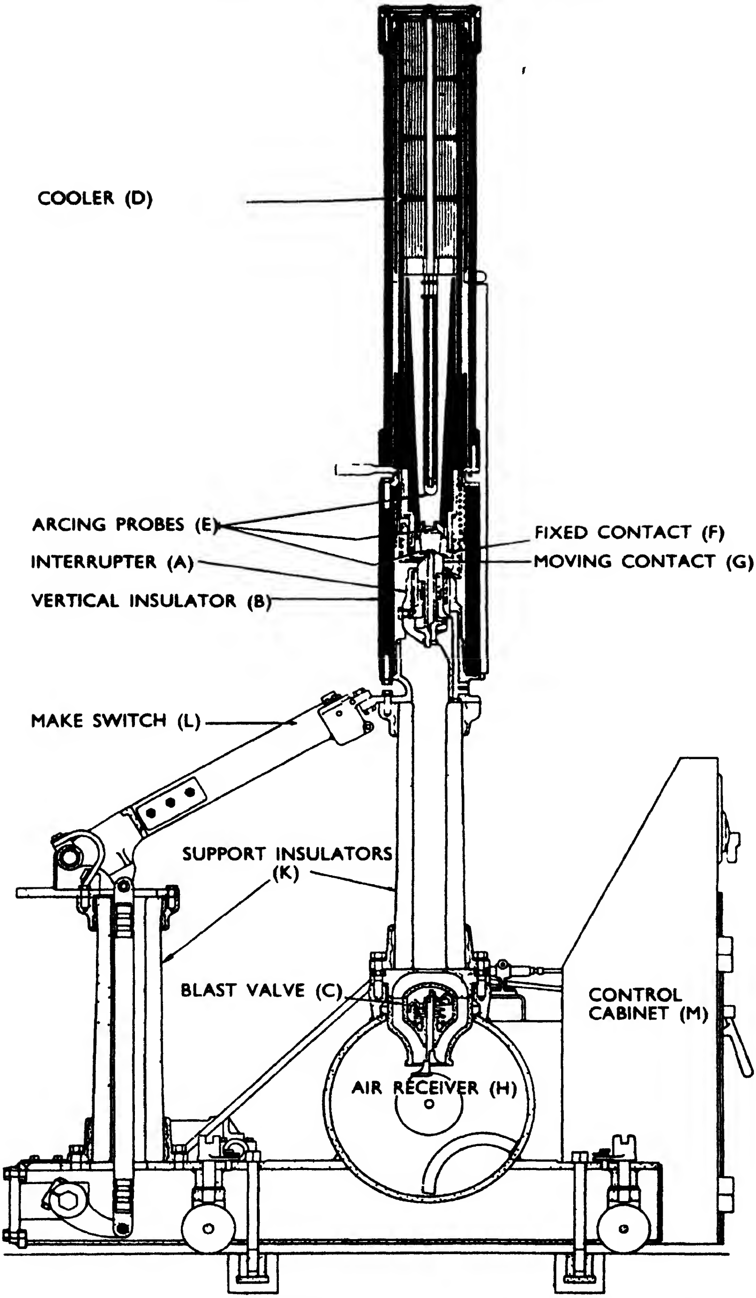


FIG. 8-16.—*Sectional arrangement of 33 kV air-blast circuit-breaker. Frame "e" (English Electric Co. Ltd.).*

Although of indoor design, an economical design of outdoor substation is achieved by accommodating each circuit-breaker in a blockhouse, a typical arrangement being that shown in Fig 8-19.

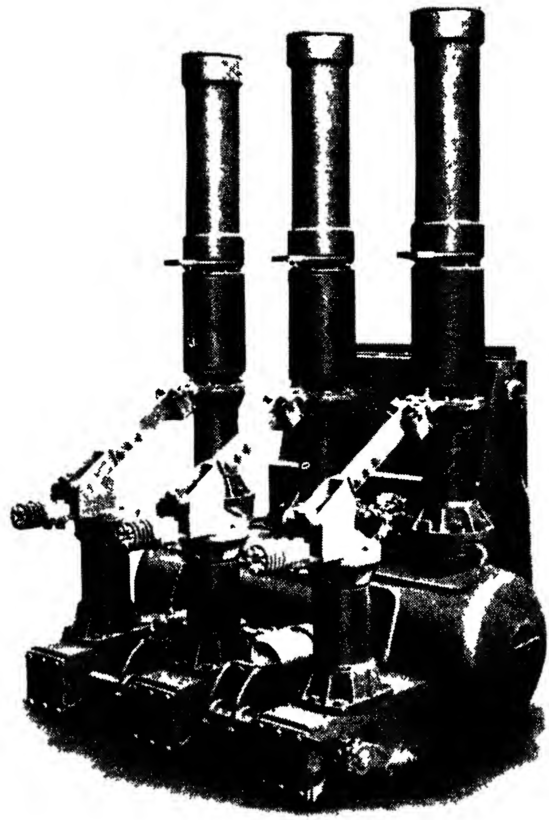


FIG 8-17 —33 *kV air-blast circuit-breaker for indoor mounting Frame "e"* *(English Electric Co Ltd)*

In an English Electric range for higher voltages (from 110 to 345 kV) multiple interrupter heads are connected in series in vertical stacks, using one stack per pole up to 165 kV and two for higher voltages, typical circuit-breakers being shown in Figs. 8-20 and 8-21

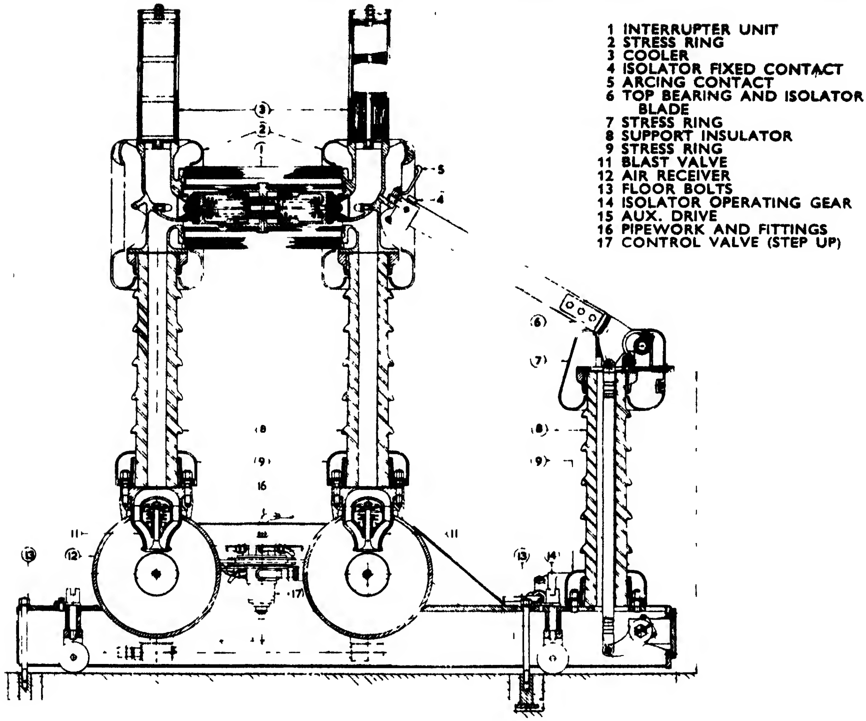


FIG. 8-18.—*Sectional arrangement of 66 kV indoor air-blast circuit-breaker Frame "c" (English Electric Co. Ltd.).*

FIG. 8-19.—*Arrangement of blockhouses for 66 kV air-blast circuit-breakers (English Electric Co. Ltd.).*

In Fig. 8-21, it will be seen that the series (make) switch takes a different form to those previously noted in that two blades are used, making contact at the centre.

It has been indicated earlier that current transformers associated with air-blast circuit-breaker installations may be either separately mounted or, where the design is suitable, within the post insulator supporting the series switch contact. Fig 8-22 shows the latter arrangement.

In this high-voltage range, the interrupter head is a standard unit as shown in Fig. 8-23, in which the main components consist of a housing containing a spring-loaded moving contact which makes contact under spring pressure with the fixed element immediately above. The piston behind the sliding contact acts as a buffer for both the opening and closing movements. When air is admitted to the interrupter head, the moving contact is forced off the fixed contact when the air pressure is sufficient to overcome the spring pressure and the blast of air is exhausted through the nozzle to the exhaust chamber above.

In the English Electric designs so far noted the interrupter head is normally not pressurised and only after receipt of a tripping impulse is the

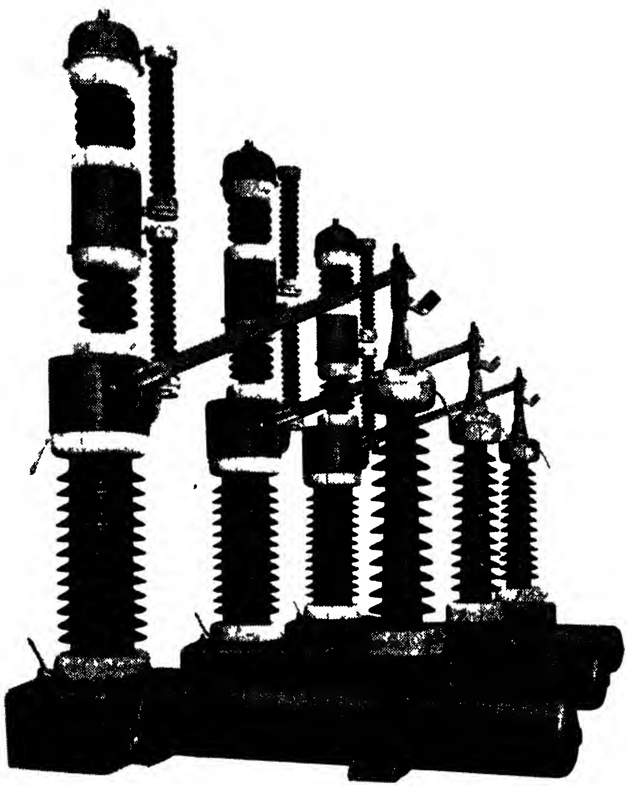


FIG. 8-20.--132 *kV air-blast circuit-breaker (English Electric Co. Ltd.).*

blast valve opened to admit air and automatically open the contacts within the interrupter head. In all designs, too, final circuit isolation has been made on a sequence operated series switch externally mounted, but air operated, and it has been noted that care has to be taken that this switch will operate successfully under the very worst icing conditions. We have

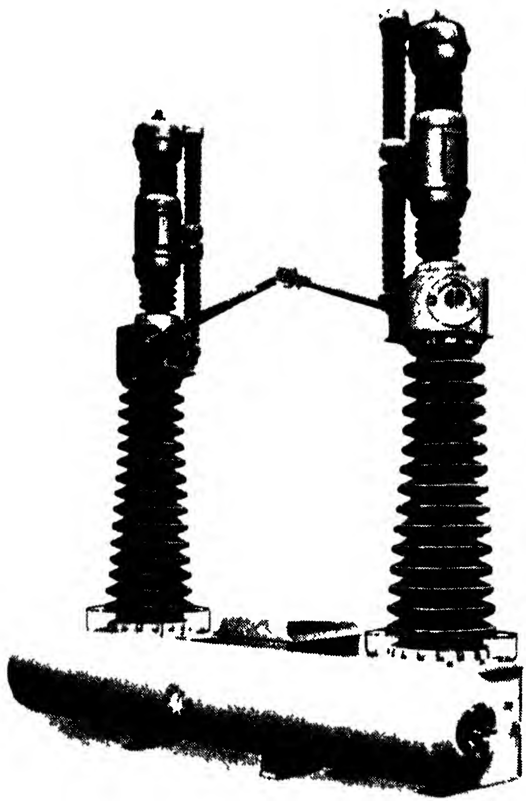


FIG. 8-21—*One phase of a three phase 220 kV air-blast circuit-breaker (English Electric Co Ltd)*

noted, however, that in some designs it is possible to dispense with this switch and to obtain full circuit isolation within the interrupter heads.

Such a design has recently been developed by the English Electric Co. Ltd., to cover all voltages from 132 kV up to 650 kV, with normal current ratings up to 4 000 amperes and breaking capacities up to 50/60 kA. This

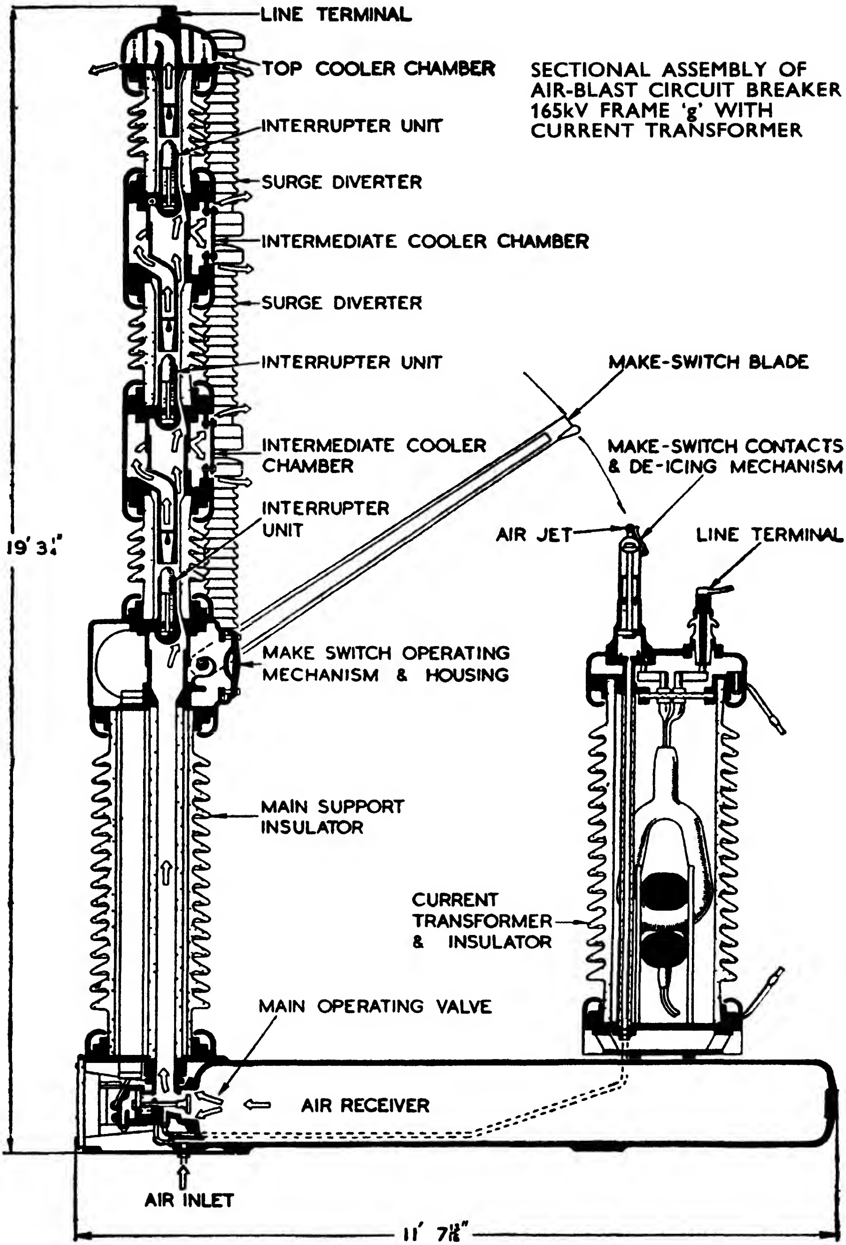


FIG. 8-22.—*Cross-sectional view of 165 kV air-blast circuit-breaker with current transformer housed in make-switch post insulator.* (*English Electric Co. Ltd.*)

circuit-breaker is permanently pressurised throughout up to the exhaust valve so that full operating air pressure is available at the contacts and there is no pressure drop or time delay in filling the support insulators as is necessary in breakers having blast valves at the receiver.

Operation on receipt of a tripping impulse in this type is mechanical and the crank and lever movements associated with the operation cause

FIG 8-24. -*Arrangement of one phase of a 400 kV 35 000 MVA air-blast circuit-breaker with interrupter heads in "Y" formation*
(English Electric Co Ltd)

air to be admitted to a piston which opens an exhaust valve This exhausts the air from one section of the contact system creating a pressure differential between the two parts and results in a moving tube and contact throat retracting, first from the main contacts to the arcing contacts and then final parting allowing the high pressure air to exhaust through a nozzle to atmosphere A feature of this design is that the arcing contacts are free to move along with the main moving contact for approximately half the travel,

and are then halted by a stop, leaving the moving contacts to complete the travel alone. By this means a greatly increased speed of opening is attained at the instant of contact separation.

The interrupter heads are arranged in "Y" or "T" formations or a combination of both to suit the rating required. A typical "Y" formation is shown in Fig. 8-24 and a "T" formation in Fig. 8-25. These illustrations clearly show the switching resistors connected across the interrupter heads for the purpose of damping any overvoltages which may occur when switching small inductive currents and, in conjunction with capacitors, ensure equal voltage distribution across the interrupters, all as previously discussed. These resistors, of the carbon ceramic linear type, are switched in and out of circuit by automatic resistor interrupters of an air-blast type and operated by differential air pressure. When the breaker is closed, the resistor interrupters are open so that the switching resistors are open-circuited. When the breaker trips the resistor interrupter is first automatically closed, thereby inserting the resistor in parallel with the main gap prior to the parting of the main contacts. When the exhaust valve resets after the main contact arc is extinguished, the resistor interrupter is automatically reopened and in so doing breaks the resistor current.

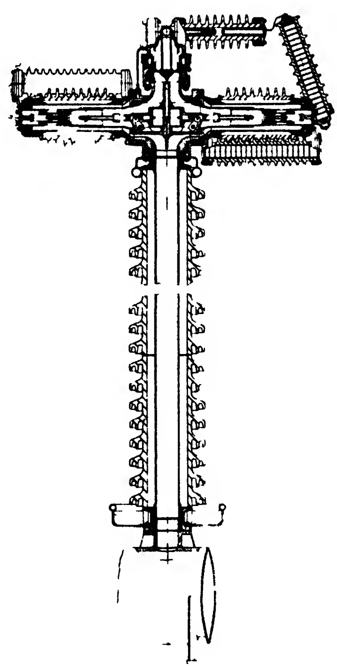


Fig. 8-25.—*Cross-sectional view of one stack of a 400 kV 35 000 MVA air-blast circuit-breaker with interrupter heads in "T" formation (English Electric Co. Ltd.).*

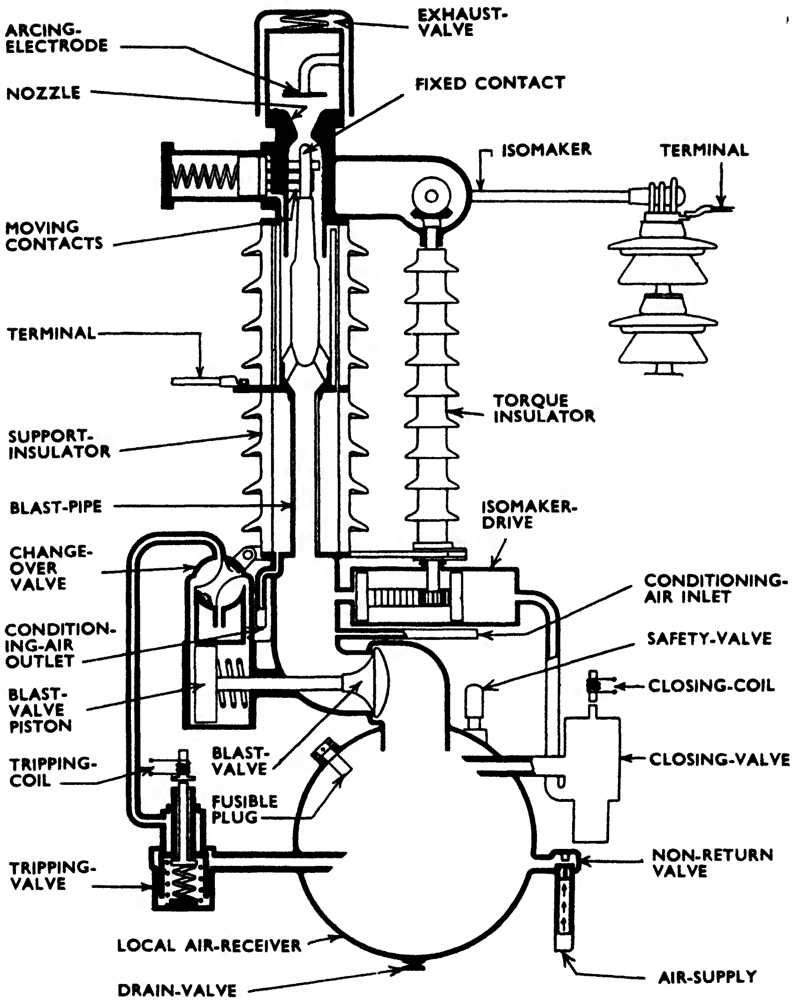


FIG. 8-26.—*Simplified diagram of air-blast circuit-breaker with side-contact "turbulator" (A. Reyrolle & Co. Ltd.).*

The range of designs by A. Reyrolle and Co. Ltd. covers voltages from 66 kV to 400 kV. The breaking capacity range required is achieved by mounting the necessary number and type of basic interrupter units in series: these interrupters have side-moving contacts, see Fig. 8-2(b), metal arcing chambers and built-in grading resistors.

The basic design is shown in Fig. 8-26 in diagrammatic form and in this illustration what we have previously called a series isolating switch is

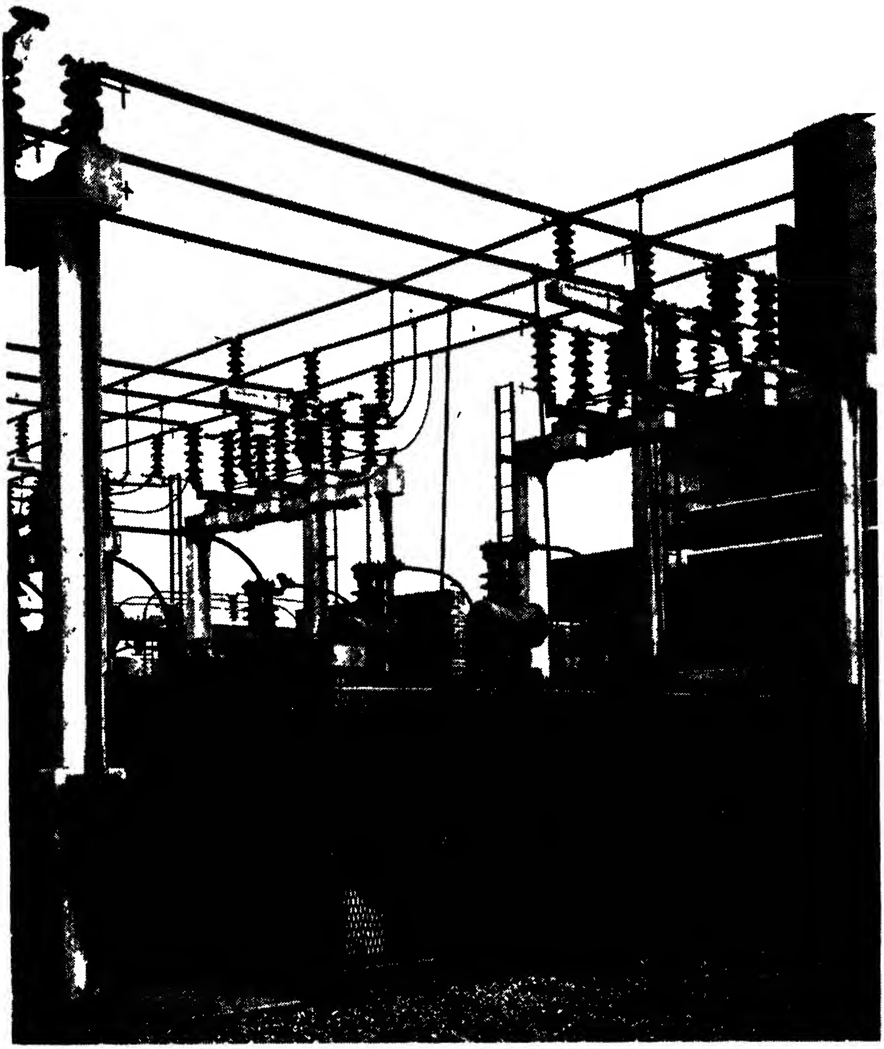


FIG 8-27 — *Typical installation of 66 kV air-blast circuit-breakers (A Reyrolle & Co Ltd.)*

described as the "Isomaker" and combines the functions of series isolation and circuit-making

To open the circuit-breaker, operation of the tripping valve is first initiated by the trip-coil plunger and air is thereby admitted, via the change-over valve, to the blast valve. The latter now opens, admitting air from the local receiver to the blast-pipe and arcing chamber

The pressure of the air so admitted causes the moving contacts (mounted on a spring-loaded piston) to open by lateral movement, thus opening the circuit and drawing an arc between the fixed contact and the extended electrode on the moving contacts. The blast of air rapidly transfers the arc to a central position through the nozzle to root on the arcing electrode, in which position it is extinguished.

Compressed air also passes to the "Isomaker" drive piston causing this switch to open and when it has reached a predetermined position it

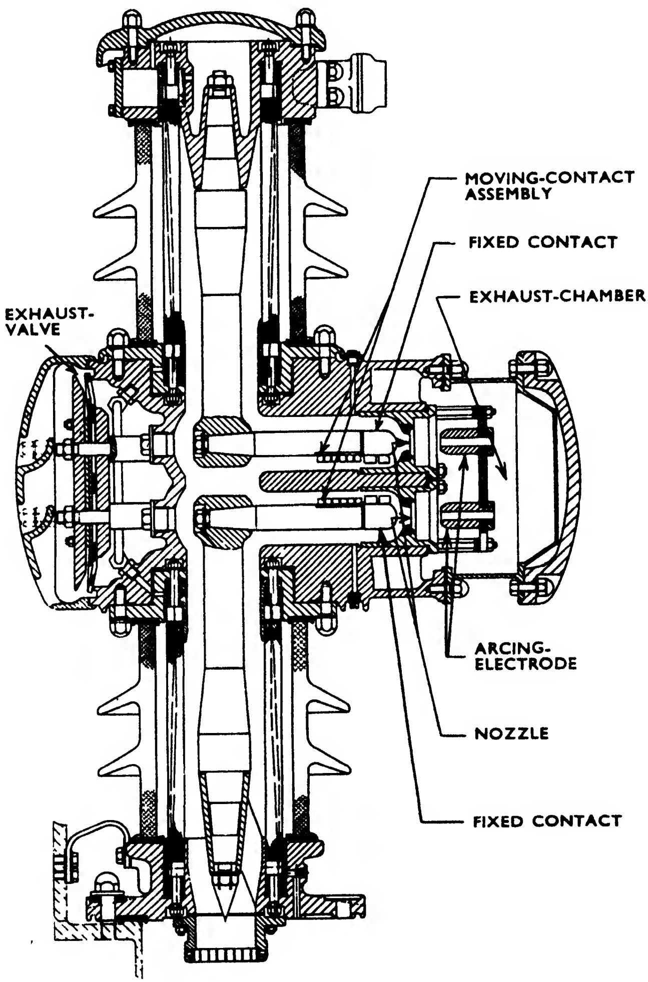


Fig. 8-28.—*Cross-sectional drawing of twin-arc air-blast "turbulator" for 66 kV service (A. Reyrolle & Co. Ltd.).*

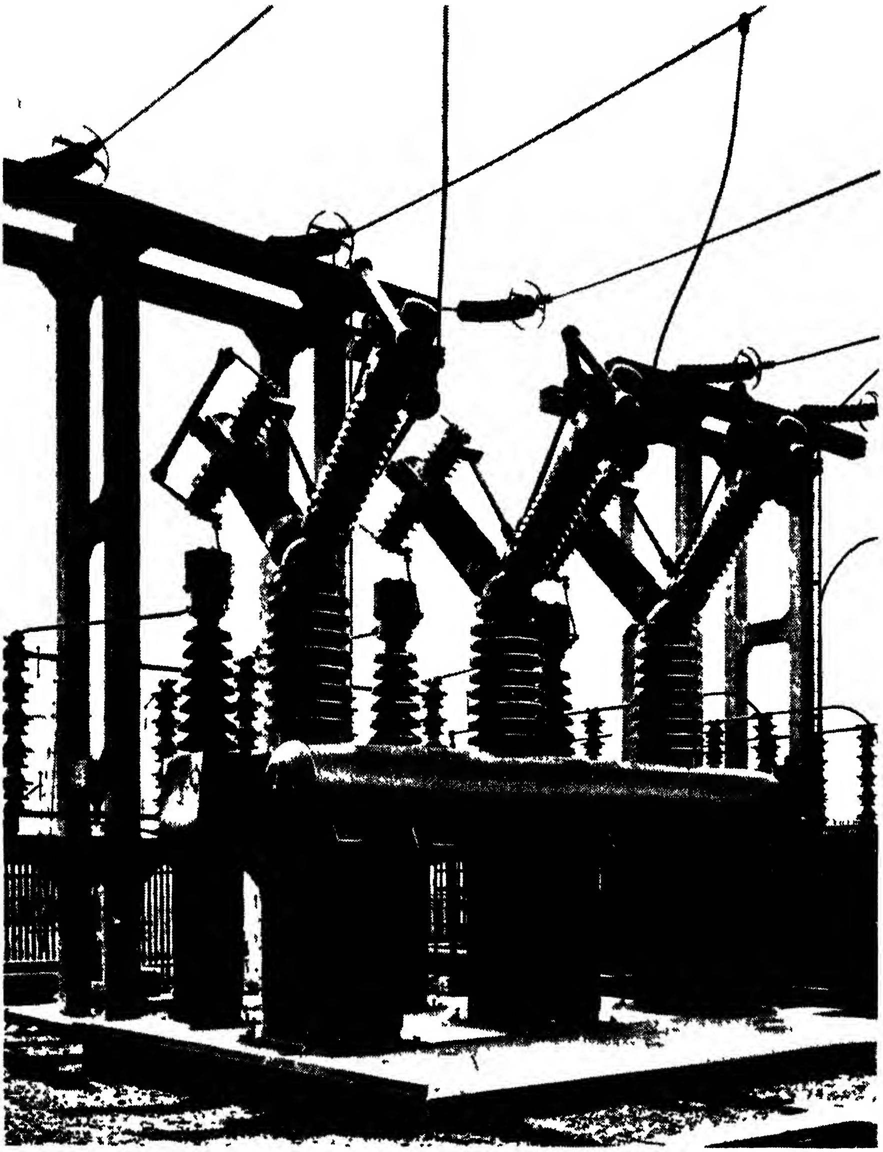


FIG. 8-29.—132 *kV air-blast circuit-breaker and associated equipment (A. Reyrolle & Co Ltd.).*

causes the changeover valve to operate and thereby reverse the supply of air to the blast-valve, causing the latter to re-close. Air is now shut off from the blast-pipe and interrupter so that the moving contacts can return, under spring-pressure, to their normally closed position, thus completing the opening operation.

To close the circuit-breaker, operation of the closing-valve admits air to the closing side of the "Isomaker" drive piston, and thereby closes the switch and the circuit is now re-established.

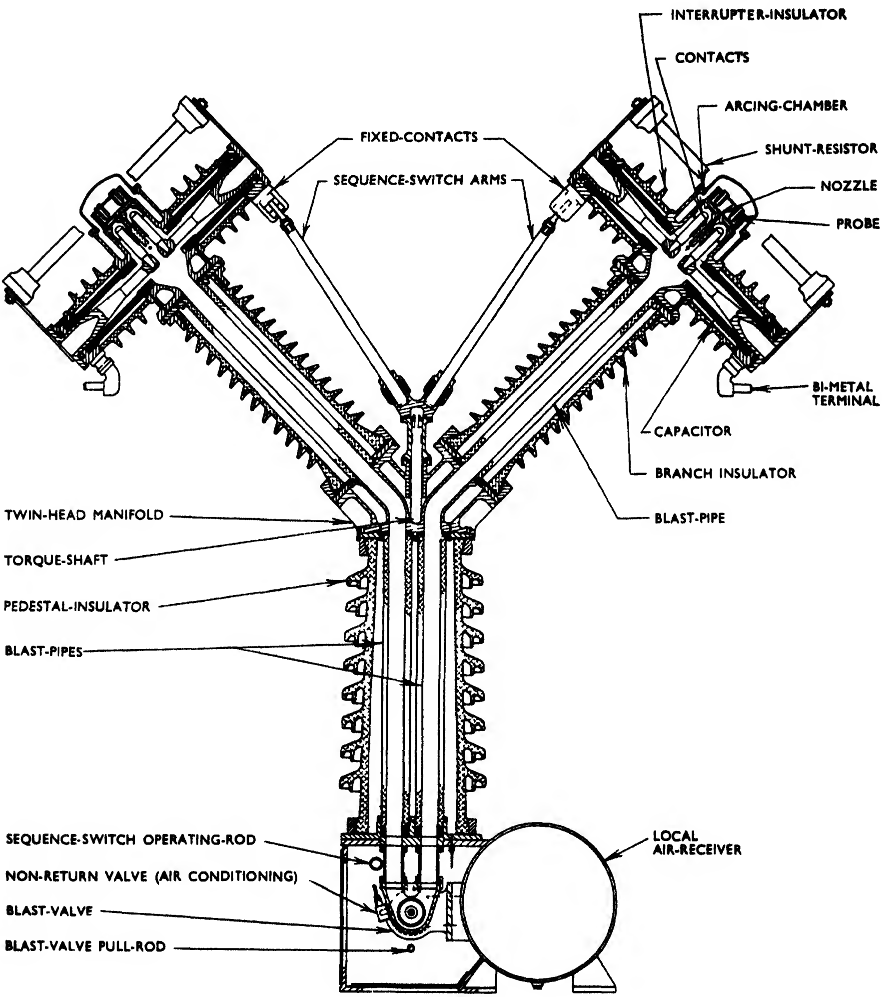


FIG. 8-30.—*Section through an air-blast circuit-breaker for 132 kV service (A. Reyrolle & Co. Ltd.).*

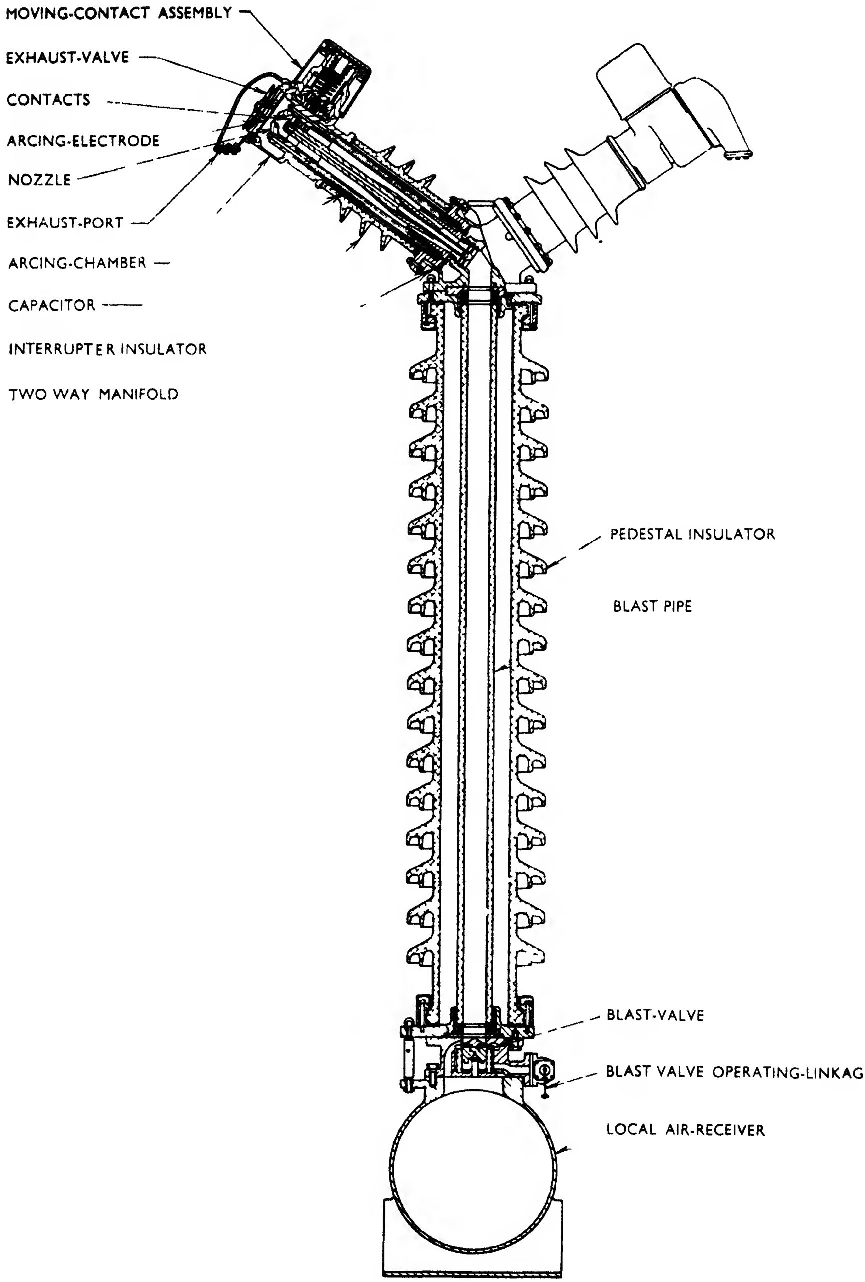


FIG. 8-31.—*One pedestal of three used per phase on a 275 kV air-blast circuit-breaker (A. Reyrolle & Co. Ltd.).*

A study of Fig. 8-26 shows an inlet for conditioning air. This is provided to avoid condensation of moisture on internal insulation surfaces and the air flow for this purpose is continuous. It must, of course, be dry air, and in order to reduce its relative humidity to a low value, the compressed air is expanded to almost atmospheric pressure.

The provision of conditioning air also offers a means whereby the air-tightness of the circuit-breaker may be checked, this being achieved by comparing the quantity of incoming and outgoing air on visual flow-meters.

In the 66 kV air-blast breaker, seen in Fig 8-27, a twin-arc air-blast "turbulator" is employed as shown in Fig. 8-28. In this arrangement the two multiple-finger contacts are solidly coupled together and are operating by a common piston

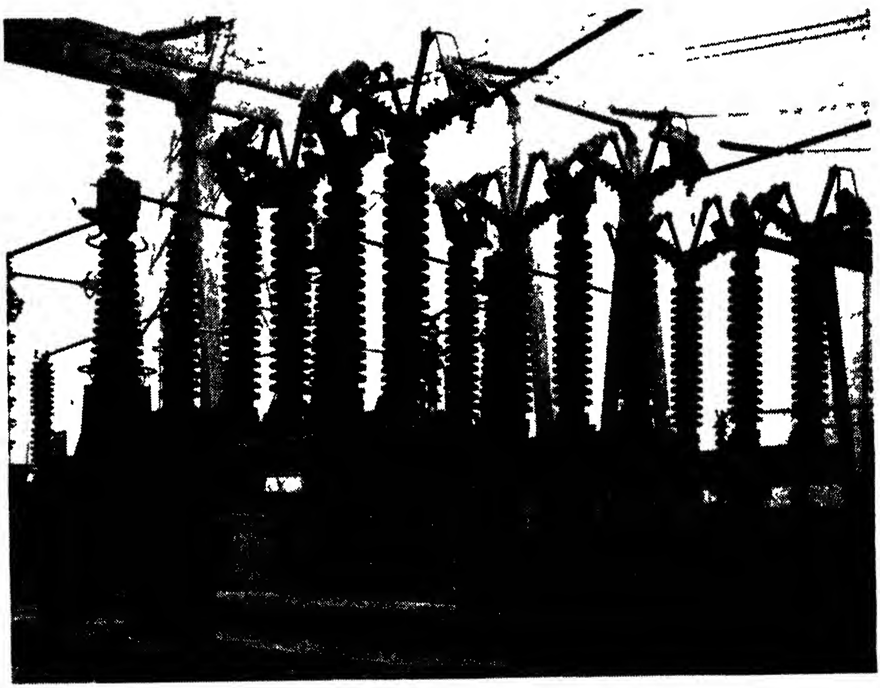


FIG 8-32 –275 *kV*, 15 000 *MVA air-blast circuit-breakers and associated equipment in service* (*A Reyrolle & Co Ltd*)

For 132 kV service, two twin-arc air-blast "turbulators" are employed in series per phase, as shown in Fig. 8-29, and in cross-section in Fig. 8-30.

A cross-sectional view of a typical pedestal as used on high-voltages (220 kV and above) is shown in Fig. 8-31, and seen in an actual installation in Fig 8-32.

For use on 400 kV systems, A Reyrolle & Co. have developed a design having an interrupting capacity of 35 000 MVA and a normal current rating

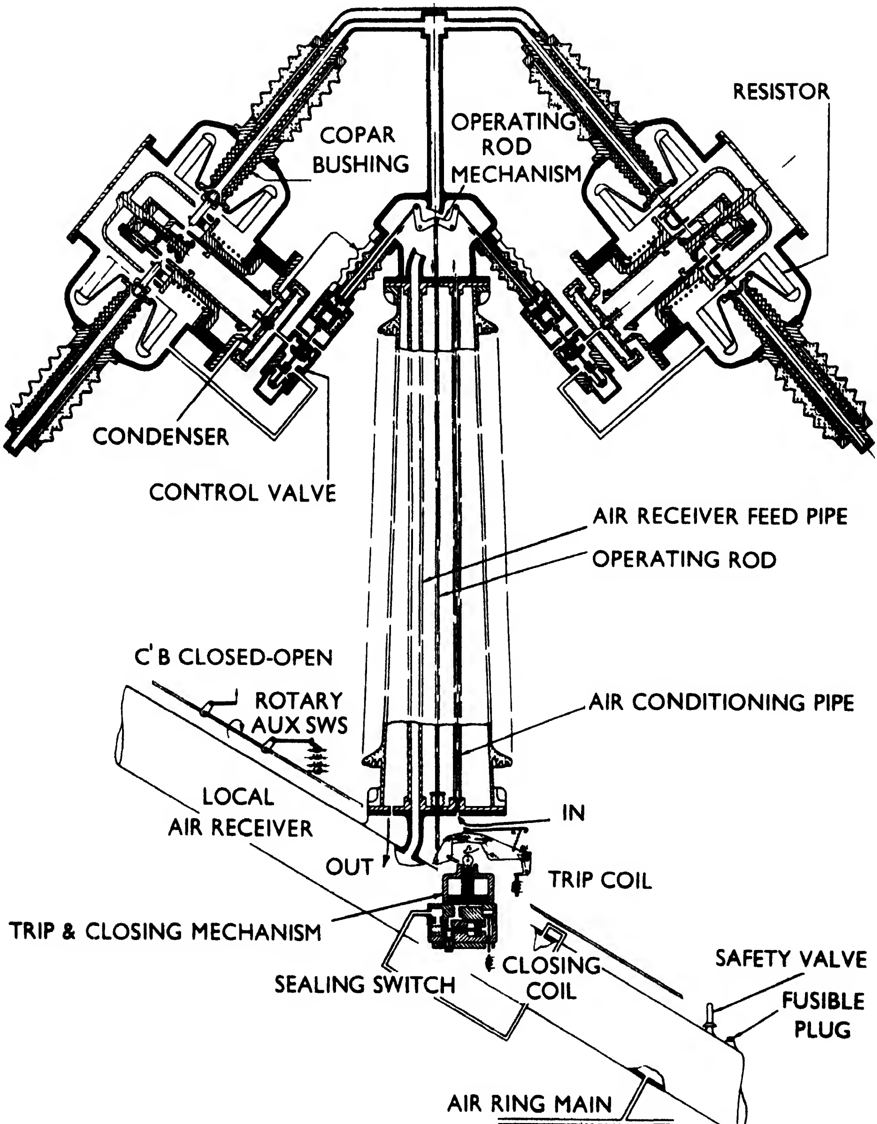


FIG. 8-33.—*Cross-sectional view of one stack of a 400 kV 35 000 MVA air-blast circuit-breaker Three such stacks are used per phase (see Fig 8-34) (A. Reyrolle & Co Ltd.)*

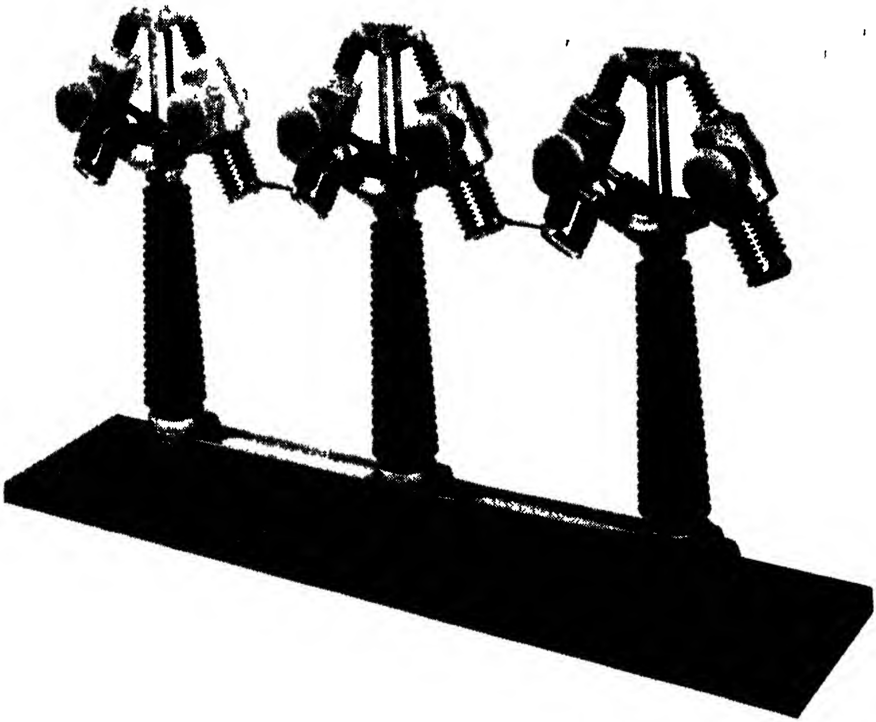


FIG 8-34 – *View of one phase of a 400 kV 35 000 MVA air-blast circuit-breaker (A. Reyrolle & Co. Ltd.)*

of 4 000 amperes in which the circuit-breaker is permanently pressurised throughout up to the exhaust valve, at 470 p.s.i. Thus, this pressure is immediately available at the contacts when they part due to a tripping impulse, eliminating the time delay and air pressure drop associated with designs having a blast valve at the local receiver which admits pressurised air only when opened

The dielectric properties of compressed air are fully utilised as a primary insulant and the circuit-breaker can be maintained in the open or closed positions without the need for series isolators (as previously described for lower voltage designs), as full isolation is obtained within the circuit-breaker itself.

From Figs. 8-33 and 8-34 it will be seen that each phase consists of three hollow support insulators mounted on a common local air receiver and that each of these insulators in turn carries two angled live-pressure-vessels, the receiver and the vessels being connected by an air feed pipe running through the hollow support insulator.

Each live-pressure-vessel houses a fixed and moving contact system (designed to give twelve breaks per phase), the exhaust and cut-off valves, and resistance switching elements comprising resistors and a switching

contact system. External capacitors are fitted to control the voltage distribution across the interrupting elements with the breaker in the open position.

The main moving contacts, which are of the multiple finger type, are carried on a free-moving piston, while cylindrical fixed contacts are formed by extensions to the conductors passing through the wall of the pressure vessel. The fixed contacts lie directly opposite an arcing nozzle. Movement of the piston to open the contacts occurs due to out-of-balance air pressures on the upper and lower faces of the piston when the exhaust valve is opened and high pressure air below the piston escapes to atmosphere. Conversely, to close the circuit-breaker, the exhaust valve chamber is sealed to atmosphere and high-pressure air admitted to lift the piston and thereby close the contacts.

Remote operation is electro-pneumatic, the required cycle being initiated by energising either the trip coil or the closing coil, both seen in Fig. 8-33 at the base of the support insulator and connected mechanically by a rod and crank system to the control valves at each live-pressure vessel.

Concurrently with the development of the air-blast circuit-breaker, attention has been directed to the plant essential for the supply of air to ensure availability at the right pressure and in sufficient quantity at all times. The quality of the air is equally important, dryness being one essential requirement so that the internal insulation of the breaker shall not be affected by moisture. Moisture in the air can be removed by refrigeration or by some drying agent or, as has been noted previously, by compression to a pressure about twice that which will be used at the breaker, the air expanding on reduction of the pressure.

Duplication of the compressor plant is normal to afford security and, to ensure the supply, the pipe system is comparable to that of an electricity supply system using one or more ring mains or a duplicate "bus pipe" system.

For indoor installations the main air storage receivers are inside. When the circuit-breakers are outside, the main receivers are also placed outside, shaded from the sun, to ensure that the temperature of the stored air does not exceed that in the local receiver, thus minimising the risk of condensation.

Fig. 8-35 shows a typical air-pressure system with ring main piping whilst Fig. 8-36 shows a system of duplicate bus pipes.

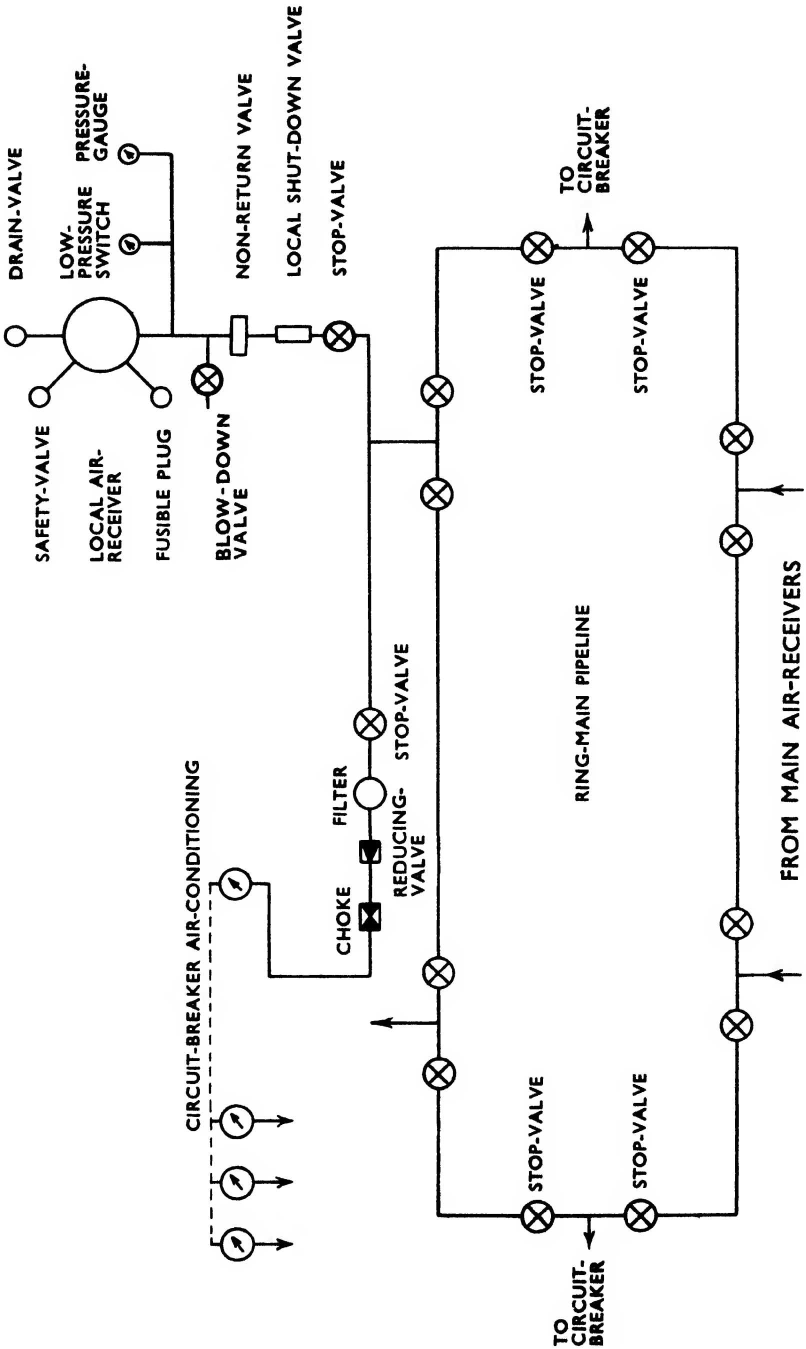


FIG. 8-35.—*Compressed air system using ring main pipe lines (A. Reyrolle & Co. Ltd.).*

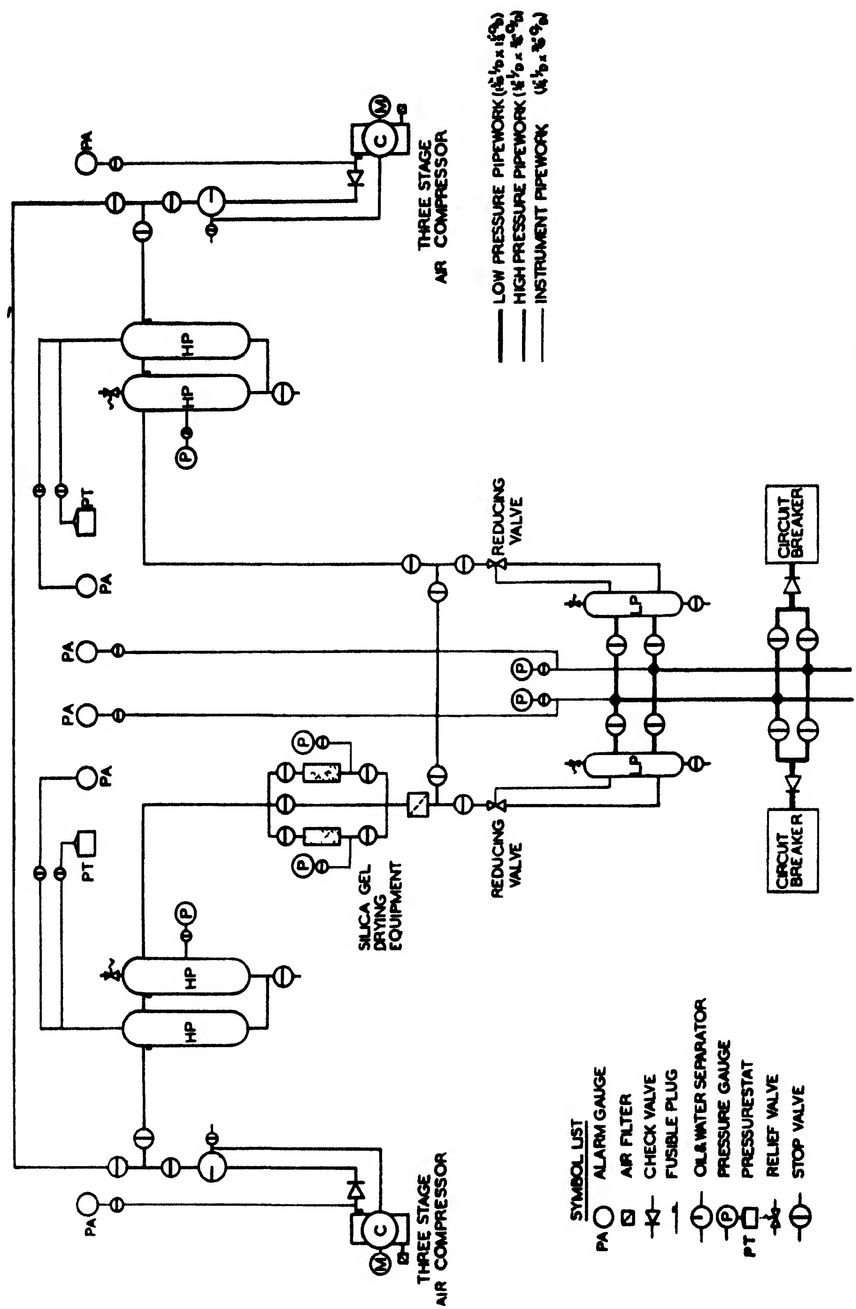


FIG. 8-36.—*Compressed air system using duplicate bus pipe line (Associated Electrical Industries Ltd.).*

BIBLIOGRAPHY

Switchgear Principles, P. H. G. Crane (Cleaver-Hume Press Ltd.).

"Air-Blast Circuit-Breakers," A. R. Blandford, "Journal I.E.E.", Vol. 90, Part II, No. 18, December, 1943.

"Restriking Voltage as a Factor in the Performance, Rating and Selection of Circuit-Breakers," J. A. Harle and R. W. Wild, "Journal I.E.E.", Vol 91, Part II, No. 24, December, 1944.

"The Influence of Resistance Switching on the Design of High-Voltage Air-Blast Circuit-Breakers," H. E. Cox and T. W. Wilcox, "Journal I.E.E.", Vol. 91, Part II, No. 24, December, 1944.

"Restriking Voltages," J. R. Mortlake, "BTH Activities," Vol. 18, No. 7, July, 1944.

"The Extinction of the Arc in Single and Multiple-Break Air-Blast High Speed Circuit-Breakers," H. Thommen, "Brown Boveri Review," November/December, 1942.

"High-Voltage Outdoor Air-Blast Circuit-Breakers," W. A. McNeill, "Engineering," August 24, 1945.

"A New 15 kV Pneumatic Circuit Interrupter," L. R. Ludwig, H. L. Rawlins and B. P. Baker, "Electrical Engineering," "Journal A.I.E.E.", Vol. 59, September, 1940.

"Design and Construction of High-Capacity Air-Blast Circuit-Breakers," H. E. Strang and A. C. Boisseau, "Electrical Engineering," "Journal A.I.E.E.", Vol. 59, September, 1940.

"The Cross Air-Blast Circuit-Breaker," D. C. Prince, J. A. Henley, and W. K. Rankin, "Electrical Engineering," "Journal A.I.E.E.," Vol. 59, September, 1940.

"Circuit Interruption by Air Blast," W. S. Edsall and S. R. Stubbs, "Electrical Engineering," "Journal A.I.E.E.," Vol. 59, September, 1940.

"Air-Blast Circuit-Breakers," W. A. Coates and C. H. Flurscheim, "The Metropolitan-Vickers Gazette," July, 1945.

"Air-Blast Circuit-Breakers," T. W. Wilcox, "Electrical Times," July 8, 1943.

"The Evaluation of Restriking Voltages," J. R. Mortlake, "Journal I.E.E.," Vol. 92, Part II, No. 30, December, 1945.

"Factors Influencing the Design of High-Voltage Air-Blast Circuit-Breakers," C. H. Flurscheim, and E. L. L'Estrange, "Journal I.E.E.," Vol. 96, Part II, No. 52, August, 1949.

"Air-Blast Circuit-Breakers for Very High Voltages," G. K. Simpson, "Journal I.E.E.," Vol. 4, No. 41, May, 1958.

"High-Voltage Air-Blast Circuit-Breakers," C. H. Flurscheim, "The Engineering Journal," (Canada), December, 1953, and "The M.V. Gazette," July, 1954.

"Air-Blast Circuit-Breakers for High-Voltage Networks," C. H. Flurscheim, "The M.V. Gazette," August, 1956.

"Some Researches on Current Chopping in High-Voltage Circuit-Breakers," A. F. B. Young, "Proceedings I.E.E.," Vol. 100, Part II, No. 76, August, 1953.

"400 kV Switchgear," Editorial article in the "Electrical Review," 13th October, 1961.

"Switchgear Trends in British Stations," R. P. E. Tabb and S. E. Newman, "Electrical Times," 21st June, 1962.

CHAPTER IX

HEAVY DUTY AIR-BREAK CIRCUIT-BREAKERS

CHAPTER IX

HEAVY DUTY AIR-BREAK CIRCUIT-BREAKERS

In an earlier chapter it has been noted that in Britain, for voltages up to 11 kV at least, the oil circuit-breaker is by far the most popular form in use, a fact attributable to the highly successful development of the type for fault interruption under severe conditions. In recent years an increasing tendency has been noticeable towards the air-break circuit-breaker, particularly for power station auxiliary services and in large industrial installations where relatively high breaking-capacity is required.

The air-break circuit-breaker in its simplest form has, of course, been used for many years on d.c. installations and on some l.v. a.c. up to about 600 volts. Relatively slow acting with fairly long arcing time, this older type employed no special means of arc-control and its breaking capacity was limited. The arc, on striking between the separating contacts, was

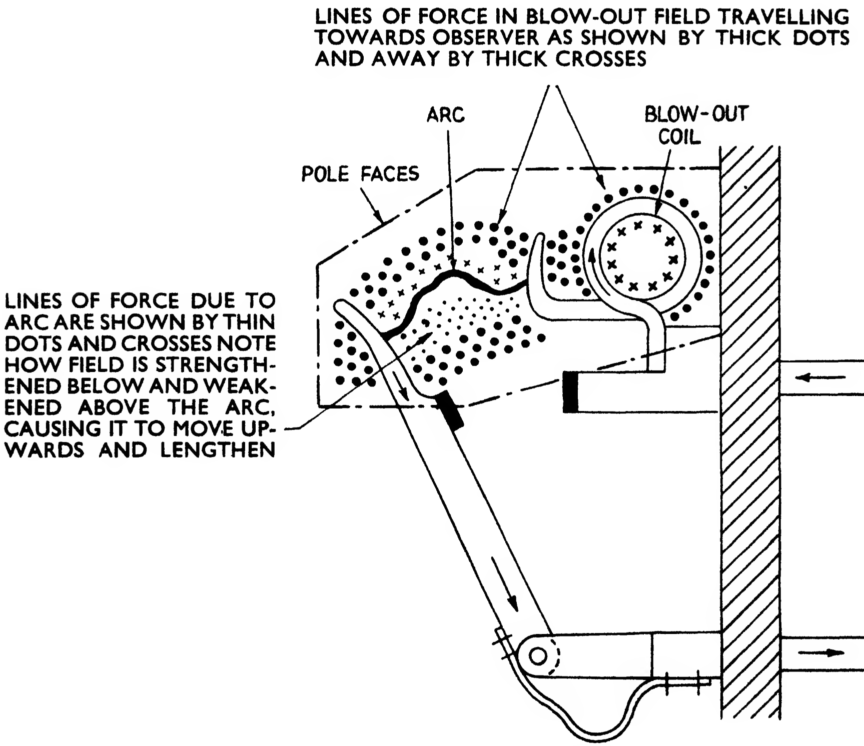


FIG. 9-1.—*Diagram showing principle of magnetic blow-out.*

lengthened by being bowed upwards due to the electromagnetic forces until it reached a point at which it could no longer be sustained by the system voltage. In some cases these forces were augmented by a magnetic blow-out derived from a suitably located series coil functioning in the manner shown in Fig. 9-1.

This fairly simple type of breaker, however, could not meet the requirements of power systems where, in the voltage range 400–600 volts, breaking capacities of 15 to 35 MVA are necessary and it was, of course, never contemplated that they could be adapted for use on higher voltages, e.g. 3·3 to 11 kV with breaking capacities of 150 to 500 MVA. Instead, new designs have been produced of a much more robust character, utilising specially designed contact systems and arc chutes, and giving high-speed operation and short-arcing times.

Such circuit-breakers, employed as they are at locations close to power sources, must, of necessity, be capable of performing no less efficiently than their counterpart the oil circuit-breaker and the short-circuit proving tests to which they must be submitted are, indeed, equal to those in B.S. 116 for oil breakers. These tests of breaking and making capacity, at low power factor and the maximum degree of asymmetry are onerous and particularly so in the lower voltage class. In the latter, the design may be regarded as only economically possible for breaking capacities of 15 MVA and upwards and this, in turn, suggests that the lower value of normal current rating will be 600 amperes or perhaps 800 amperes These limitations lead also to the need for power operated closing mechanisms (solenoid or spring) for short-circuit values above 22 000 amperes (symmetrical r.m.s.) and while hand operated mechanisms do exist, the majority of designs employ other forms in preference, in line with British Standard recommendations.

At the lower voltages, too, it is possible in most designs to use series (whole current) overload coils for currents up to about 800 amperes and it must be borne in mind that for low currents, say up to 100 amperes, the interrupting capacity of the breaker as a whole will be determined by the ability of the coils to withstand the effects of short-circuit current. In other words, while a breaker without series overload coils may have a breaking capacity of, say, 30 MVA, the effect of adding series coils of low current rating may reduce the overall ability to a much lower figure, perhaps as low as 7·5/10 MVA. This feature is not, of course, peculiar to the air-break circuit-breaker; it applies equally to the oil-break type.

The design problems associated with the air-break circuit-breaker at 3·3 kV and above will be very different to those which concern medium-voltage designs. Not only is there the problem of higher insulation strengths but, more important, that of interrupting in air at atmospheric pressure.

In this chapter we shall be concerned only with designs to meet the requirements of heavy duty,* considering first those for the voltage range 400/660 volts and later those for 3·3 to 11 kV.

In the medium voltage range, an elementary arrangement is shown diagrammatically in Fig. 9-2, comprising a contact system of separate main and arcing contacts, an arc chute with splitter plates and a pair of arc runners, the purpose of the latter being to assist the movement of the arc into the chute and into close contact with the splitter plates.

Mainly classes B and C. ASTA No. 16

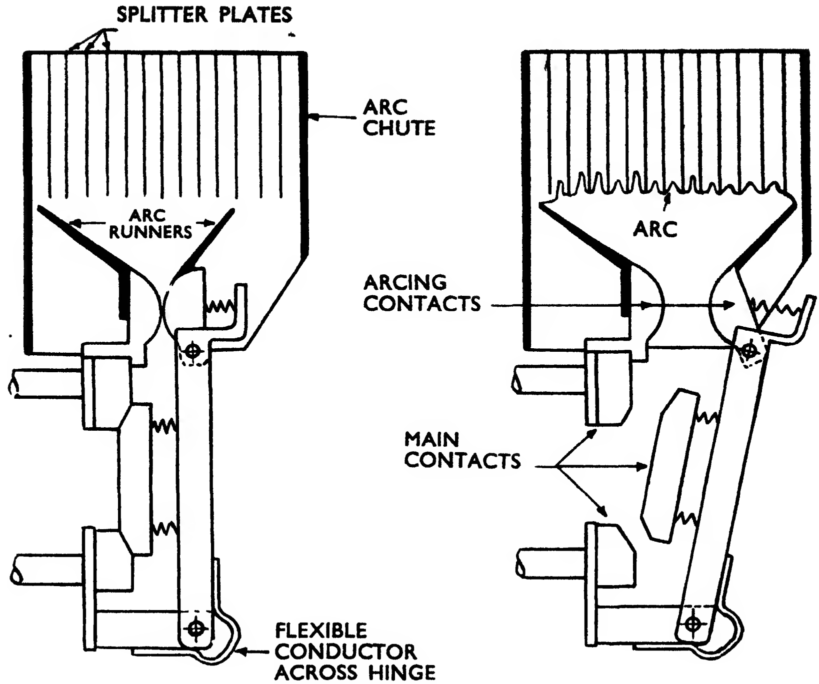


FIG. 9-2.—*Elementary arrangement of air-break circuit-breaker.*

When an arc is drawn at the arcing contacts, it is forced upwards by its own electromagnetic forces and by thermal action, its roots travelling rapidly along the arc runners. The splitter plates tend to break up the arc and lengthen it while at the same time the plates cause cooling and de-ionisation to the point when the arc is readily extinguished at an early current zero. The plates also help to reduce the velocity of the expelled arc products to atmosphere above the arc chute.

We shall see later in describing some of the available designs, that there are numerous variations on the simple basic form, Fig. 9-2, as for example the use of steel or copper splitter plates in certain cases and insulated, arc-resisting plates in others. The arc runners in one design are fixed within the structure of the arc chute instead of being part of the contact structure. In yet other designs, the arc runners are simply extensions of the arcing contacts.

All designs are of the single-break type and it is particularly important that, if there is any possibility of a break at the hinge contacts, the continuity of the current path being ensured by flexible conductors or other means. In some designs this problem is avoided by having no contact breaking elements at the hinge point.

The advantages of the air-break circuit-breaker are that the elimination of oil reduces the maintenance necessary, particularly if repeated operations

are essential, that the total break and arcing times are much shorter than are possible in plain-break oil circuit-breakers, and that unlike so many low-voltage oil circuit-breakers, the air-break circuit-breaker can be housed in flush-fronted enclosures of more pleasing appearance and in double tier formation, while retaining their valuable draw-out features.

In addition, access to the contacts for inspection or replacement is more readily obtained than when an oil tank has first to be removed.

A typical air-break circuit-breaker of the type discussed is that shown in Fig. 9-3, one of a range made by the General Electric Co. Ltd., with current ratings of 800–3 000 amperes, and a breaking capacity of 31 MVA at 400–550 volts.

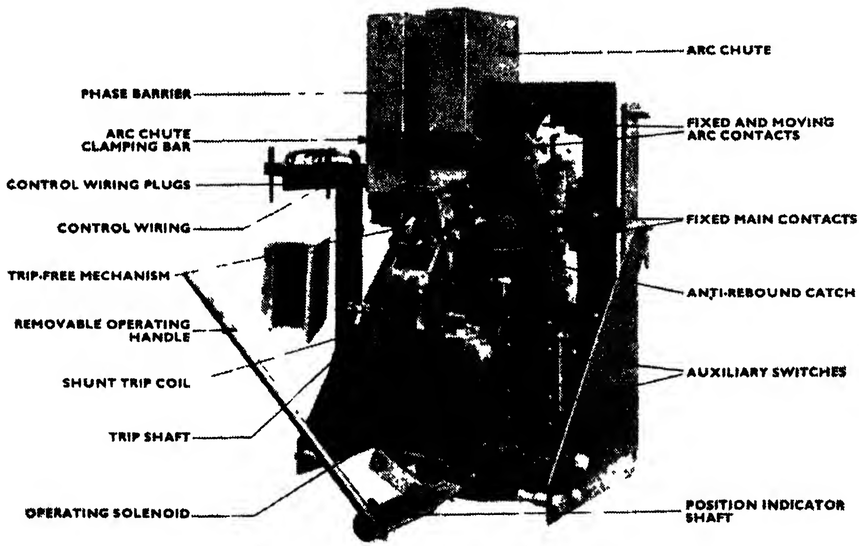


FIG. 9-3.—800 *ampere air-break circuit-breaker with one arc chute removed* (*The General Electric Co. Ltd.*).

In this design, both the main and arcing contacts are of the butt type, the main contacts being faced with silver and the arcing contacts with an arc-resisting alloy to reduce arc erosion. The box-shaped arc chute is made of arc-resisting material with splitter plates shaped to produce tapered slots as shown in Fig. 9-4.

Tests on circuit-breakers in this range show that both the total break time and the make time are less than 4 cycles and at the higher values of short-circuit current, arcing times are generally less than one cycle. The ability to break low values of current such as transformer magnetising currents is demonstrated in the curve Fig. 9-5, which shows the relation between arcing time and the current interrupted by a 2 000 ampere circuit-breaker.

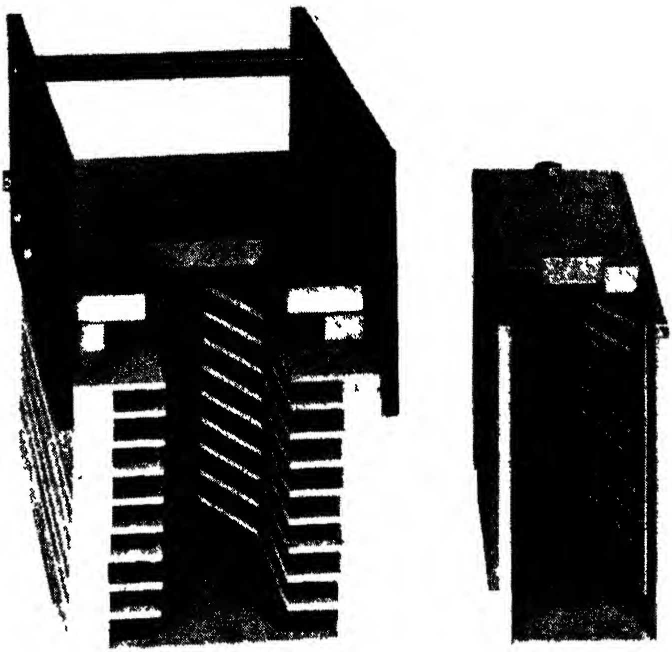


FIG. 9-4.—*Arc chutes for 2 000 ampere (left) and 800 ampere (right) air-break circuit-breakers (General Electric Co. Ltd.).*

A range of circuit-breakers, made by Associated Electrical Industries Ltd., includes current ratings 600–2 400 amperes with breaking capacities up to 31 MVA at 415 volts. A 1 600 ampere unit is shown in Fig. 9-6.

In these circuit-breakers, one set of contacts only are used to serve both the main current carrying and arcing duties for normal ratings up to 800 amperes. Above this, separate sets of contacts are used for the two duties. Advantage is taken of the electromagnetic forces arising from heavy short-circuit currents by designing the contact system in a way such that these forces tend to increase the contact pressure, a feature shown in Fig. 9-7.

The arc chute employed is of novel construction in that a number of copper rods are fixed between the two side plates of the arc chute box for the purpose of cooling and controlling the arc. A partly dismantled arc chute is shown in Fig. 9-8 to illustrate the construction and this also shows how two wide copper strips are built in to act as arc runners. A steel strip on the centre line of these runners serves to centralise the arc in the chute.

A design which has the arc runners forming part of the contact system is one by W. Lucy and Co. Ltd., the runners on the moving contacts being arranged to move with them. The complete contact system is shown in

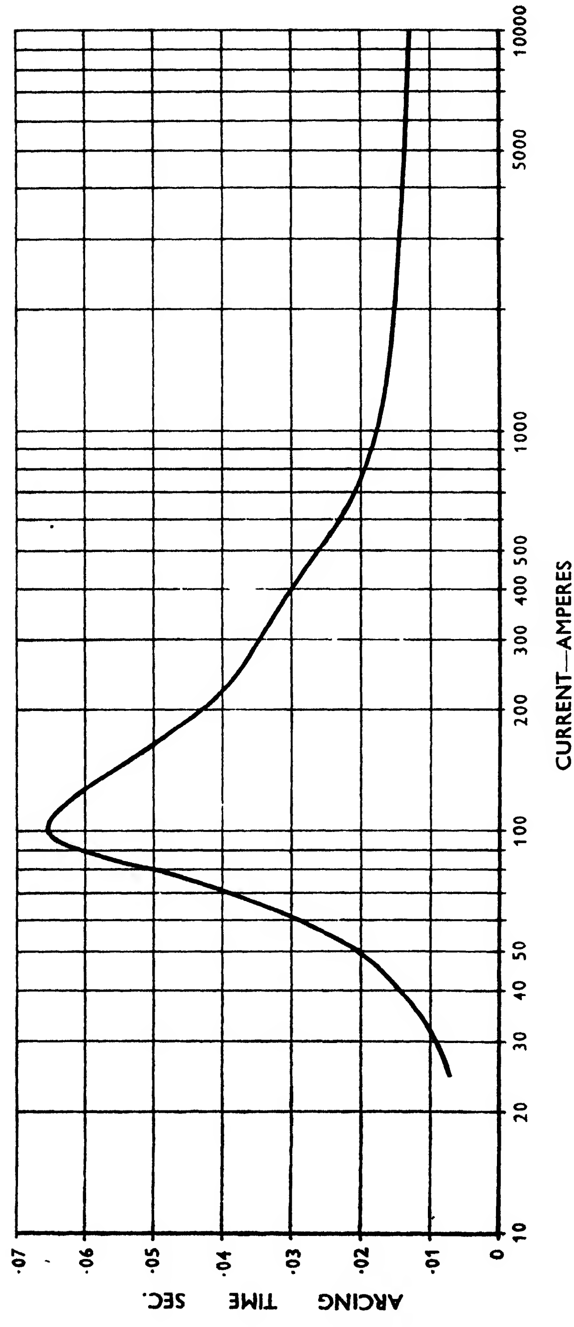


Fig. 9-5.—*Relation between arcing time and current interrupted, on a* 2 000 *ampere air-break circuit-breaker (The General Electric Co. Ltd.).*

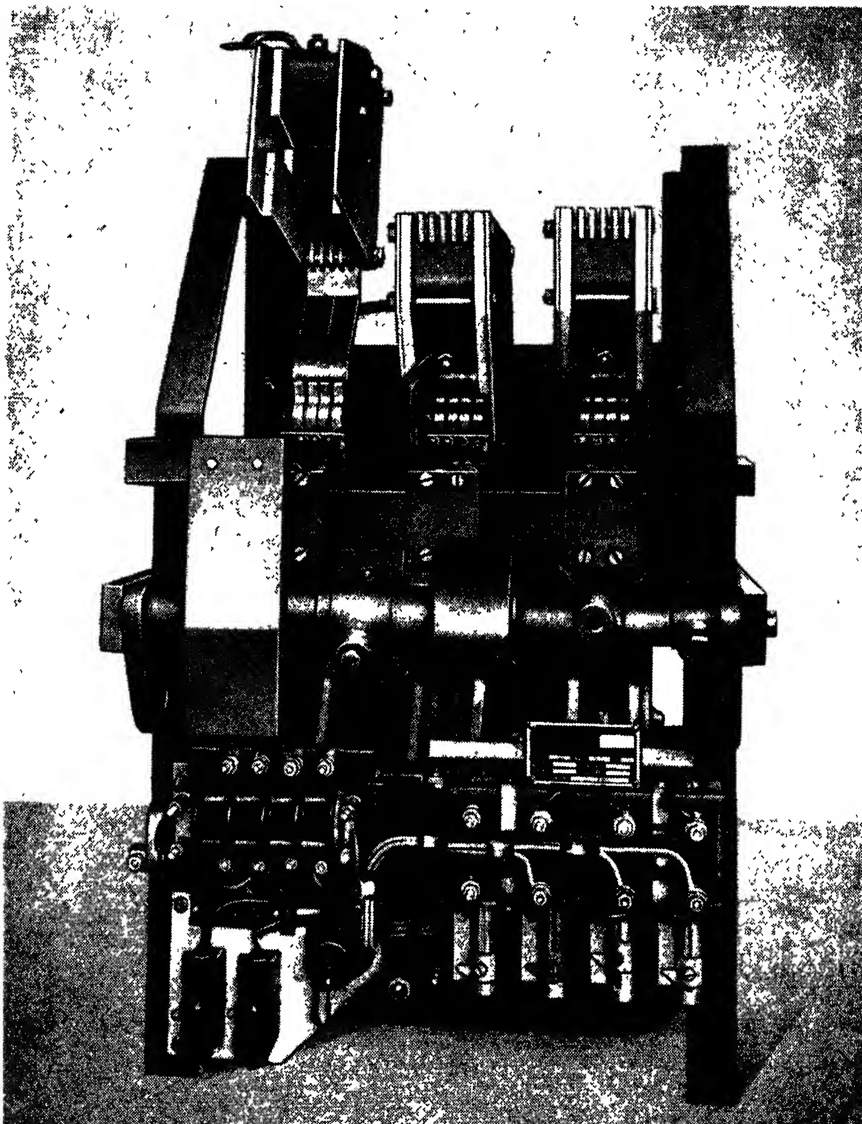


Fig. 9-6.—1 600 *ampere air-break circuit-breaker with one arc chute raised and phase barriers removed* (*Associated Electrical Industries Limited*).

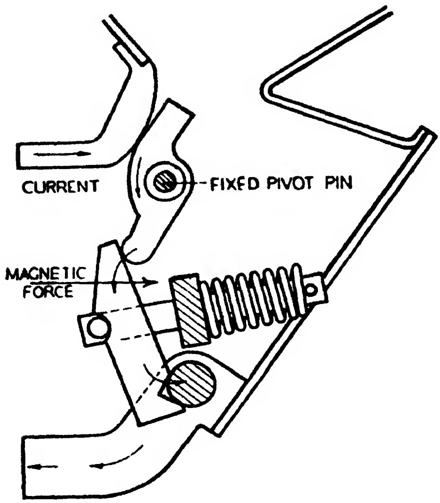


FIG. 9-7.—*Contact system for air-break circuit-breaker in Fig. 9-6 (Associated Electrical Industries Limited).*

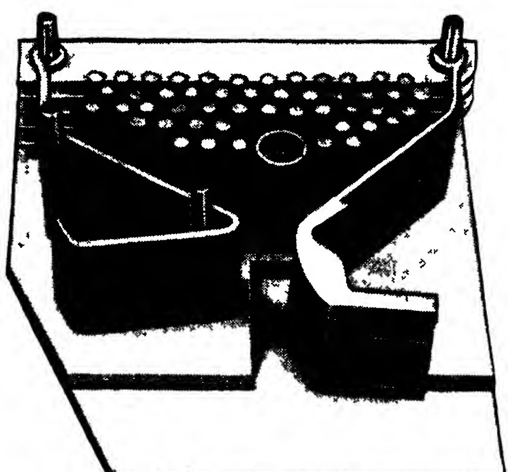


FIG. 9-8.—*Partly dismantled arc chute for the breaker in Fig. 9-6 (Associated Electrical Industries Ltd.)*

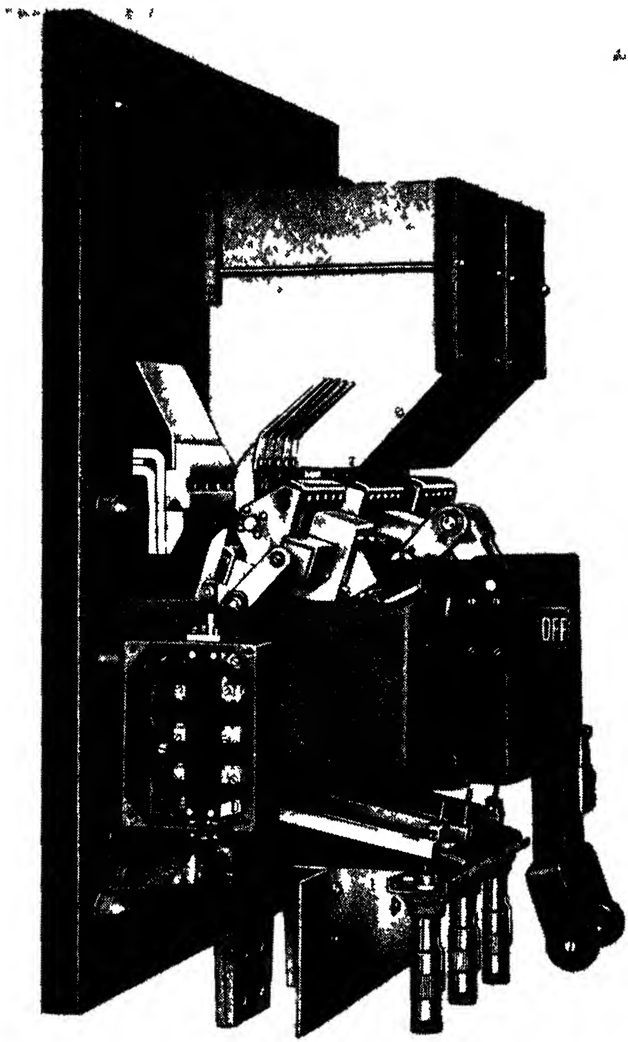


FIG 9 9 —*Air break circuit breaker in closed position with one arc chute removed* (*W Lucy & Co Ltd*)

Figs 9-9 and 9-10 in the closed and open positions respectively, with one arc chute removed

In the contact system shown it will be seen that there are what are called "secondary" contacts These "secondary" contacts are so arranged that they break *after* the main contacts and *before* the final arcing contacts The

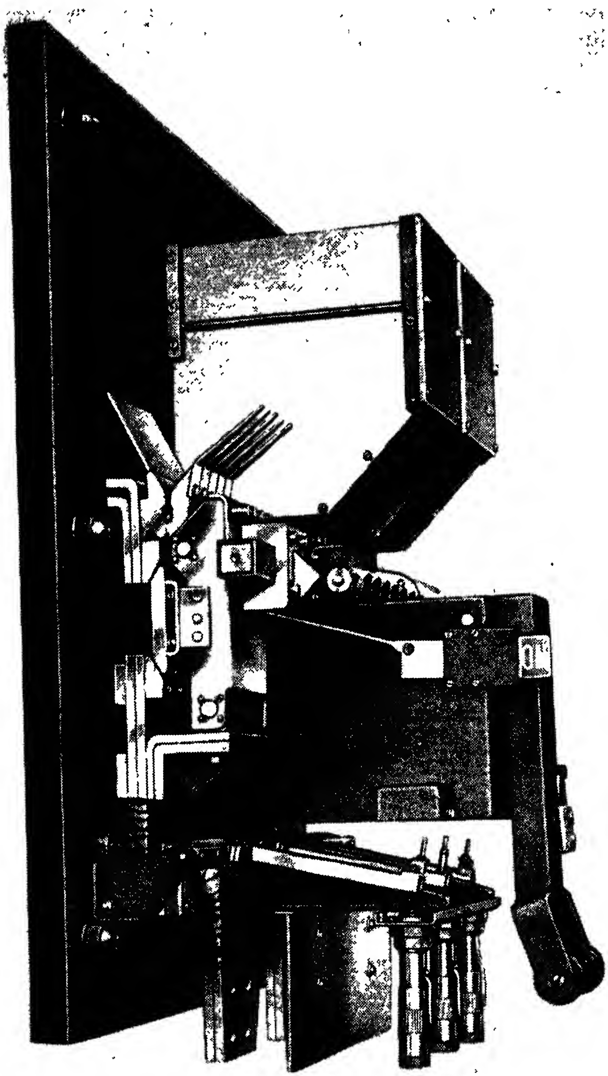


FIG. 9-10.—*Air-break circuit-breaker in open position with one arc chute removed. (W. Lucy & Co. Ltd.)*

design is rated at 26 or 31 MVA at 415 volts with arcing times of less than ½ cycle at 100 per cent breaking capacity duty, and although shown in the illustrations as mounted on panels, the breakers can be cubicle mounted in draw-out or non-draw-out arrangements.)

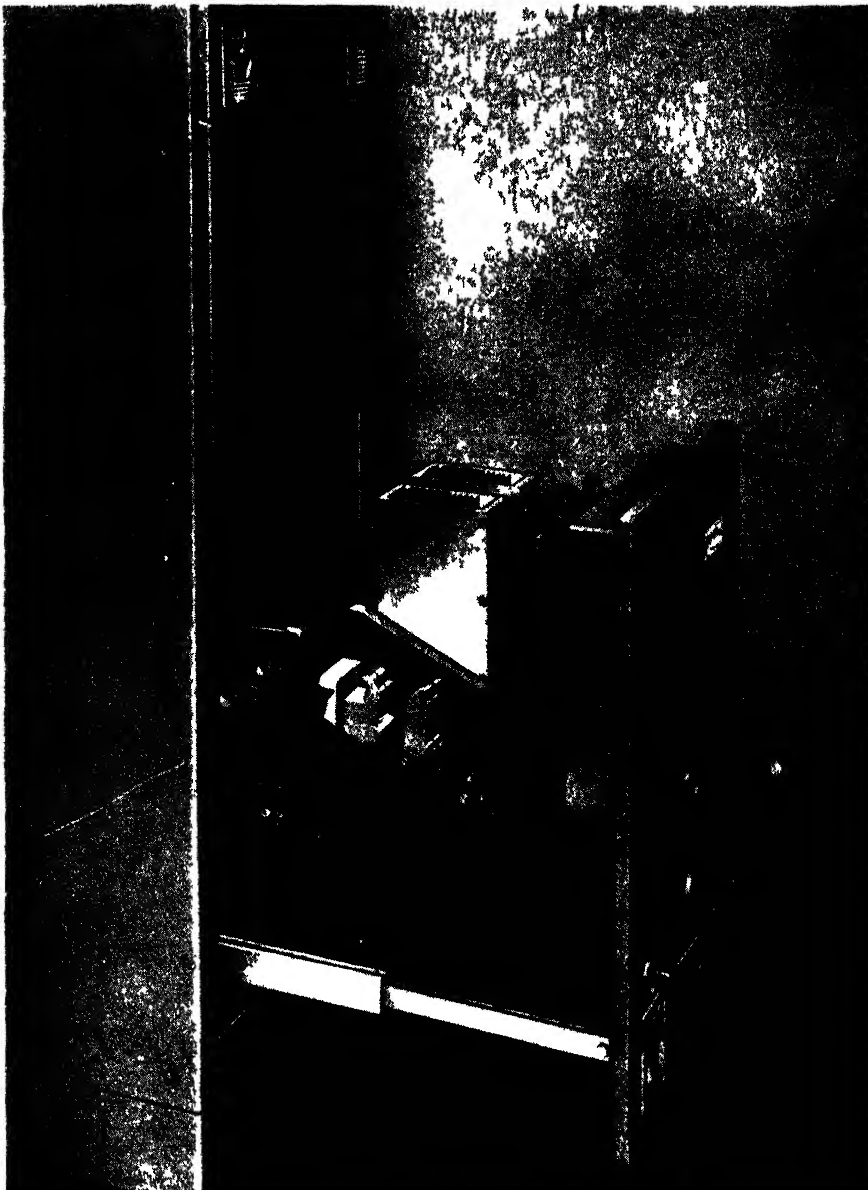


FIG 9-11 —*Air-break circuit-breaker in open position, one arc chute removed to show contact system (G Ellison Ltd).*

Fig. 9-11 shows a design by George Ellison Ltd., in which the main and arcing contacts (fixed and moving) are one-piece components, the arcing area being faced with silver tungsten to reduce arc erosion. As in most designs, the arcing contact makes first and breaks last, but in this design the arcing contact is arranged to re-open after the mains contacts are fully closed. The advantage of this arrangement is that, if when closing on to a fault, any welding occurs at the arcing contacts, the re-opening action is such as to break the weld. It also means that the arcing contacts play no part in the normal current carrying function. Similar contacts are also used at the hinge point, but to ensure that no current is broken here, the fixed and moving elements are bridged by flexible conductors.

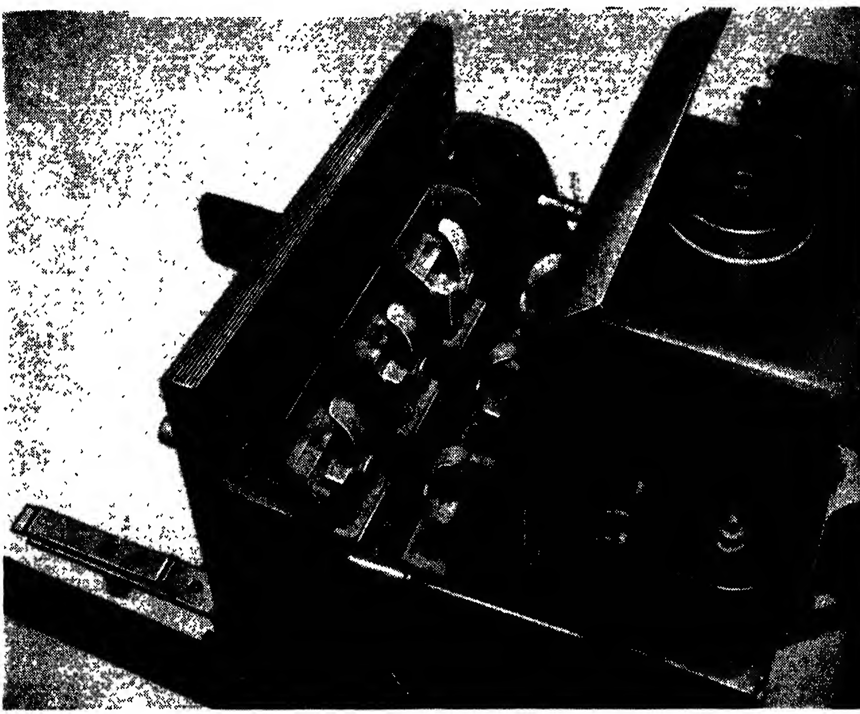


FIG. 9-12.—1 600 *ampere air-break circuit-breaker with arc chutes removed to show butt type contacts with arcing horns* (*The English Electric Co. Ltd.*).

The upper edges of the arc chute splitter plates can be seen in Fig. 9-11. Two current ratings of 800 and 1 600 amperes are employed with breaking capacities of 26 MVA Class B and 31 MVA Class A, at 415 volts.

The contact system in the English Electric design is shown in Fig. 9-12, the contacts, both main and arcing, being of the butt type with extended tips and serve as arc runners to assist the arc into the splitter-type arc chute. The splitter plates are made of steel and these, due to magnetic interaction

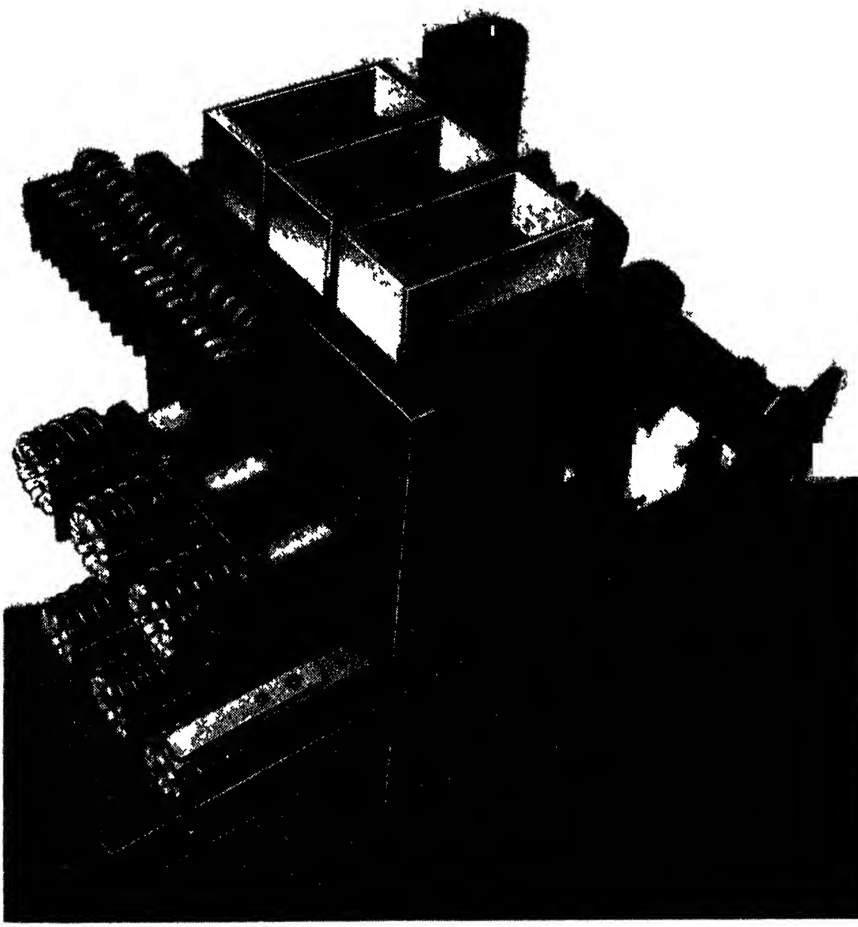


FIG 9 13—*Rear view of circuit breaker shown in Fig 9 12, with arc chutes fitted This view also shows the cluster type isolating contacts and the auxiliary contacts* (*The English Electric Co Ltd*)

with the arc field, ensure that the arc is drawn rapidly upwards to be broken up and cooled to extinction A rear view of a circuit breaker from above is shown in Fig 9 13

Three current ratings are used, 800, 1 600 and 3 000 amperes having a breaking capacity rating of 31 6 MVA at 415 volts

In their design, A Reyrolle & Co Ltd employ a contact system in which the moving element is a hinged blade which mates with fixed contacts of the self-aligning and self-gripping finger type Extended sections of both the moving blade and fixed fingers serve as arcing contacts and these are tipped with special arc-resisting metal In addition, a pair of intermediate

contact fingers are used to facilitate the transfer of current from the main contacts to the arc contacts and thus prevent burning of the silver facings on the main contacts. Fig. 9-14 shows a front view of a 1 200 ampere circuit-breaker with one arc chute removed to show the contact system as described, the range including three current ratings of 1 200, 1 600 and 2 400 amperes with breaking capacities up to 31 MVA at 415 volts

It will be clear from what has been indicated that in the medium-voltage range, the air-break circuit-breaker has been developed mainly to cover heavy-current applications and where the breaking-capacity requirements are in the range 25 to 31 MVA at 415 volts Such conditions are those regularly met in power station auxiliary services and in the larger industrial plants

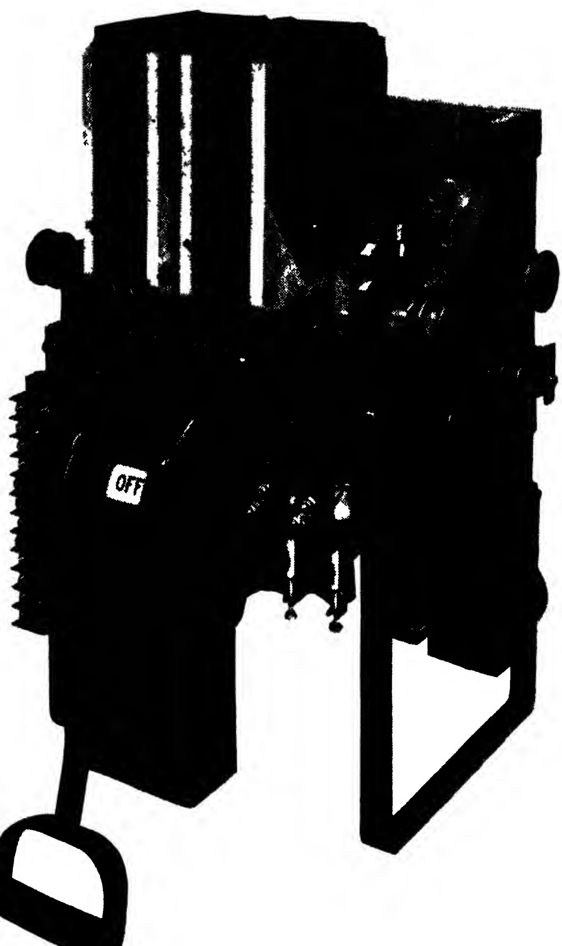


FIG. 9-14.—*Front view of air-break circuit-breaker with one arc chute removed (A. Reyrolle & Co. Ltd.).*

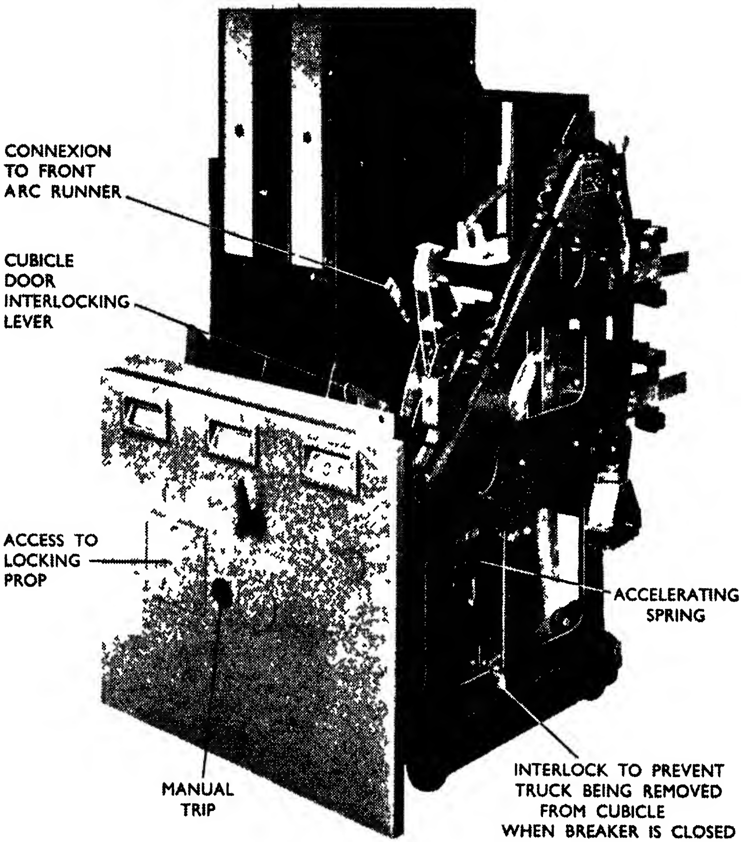


FIG. 9-15 —3·3 *kV air-break circuit-breaker on truck. One arc chute removed (The General Electric Co. Ltd.).*

It is in these two fields also that the development of the air-break circuit-breaker in the voltage range 3·3 kV to 11 kV has received its greatest impetus and in power station practice, particularly, the increasing size of power units has demanded higher powered auxiliary services beyond the recognised economic limits for medium voltages. The first step for dealing with these increased powers was to choose 3·3 kV for all auxiliary services above a certain h.p. and it was at this voltage that air-break circuit-breakers in the higher voltage range were first developed. Later developments brought in 6·6 kV designs and much more recently an 11 kV development has been noted.

At these voltages, breaking-capacity ratings of 150/250 MVA at 3·3 kV and 500 MVA* at 11 kV are required to meet service conditions, ratings

* *The increasing size of individual generator units would indicate that 750 MVA at 11 kv may be essential in the future*

which involve the interruption of 26300/43800 amperes at 3·3 kV and 26 300 amperes at 11 kV, both values being r.m.s. symmetrical. It is obvious that to interrupt such currents at these voltages in air at atmospheric pressures requires considerable knowledge of the behaviour and control of arcs in arc chutes based on fundamental data obtained from intensive research. The resulting circuit-breaker may be quite large and, in particular, the arc chute can be quite a high structure. When mounted in a cubicle (see example Fig. 10-19 in Chapter X) means to exhaust the products of arcing to atmosphere above the arc chute must be provided.

Figs. 9-15, 9-16 and 9-17 relate to one 3·3 kV design showing, respectively, a complete circuit-breaker, a close-up view of the contact structure and an inside view of an arc chute.

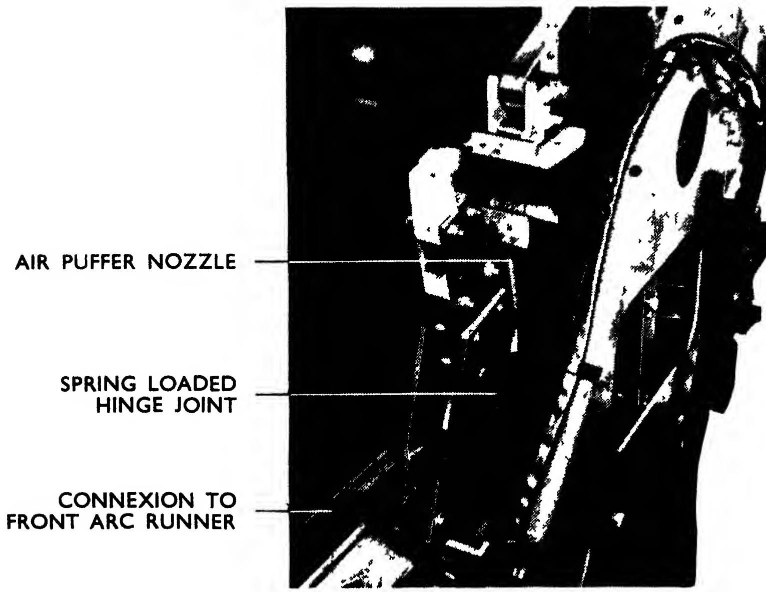


FIG. 9-16.—*Contact structure of the circuit-breaker shown in Fig. 9-15 (The General Electric Co. Ltd.).*

In this design the high-pressure main butt contacts comprise an upper fixed contact block carrying multiple spring-loaded contact fingers, with which contact is made by a block carried on the pivoted moving contact arm. The arcing contacts are also of the high-pressure butt type, the fixed fingers being pivoted and spring-loaded. The main and arcing fixed contacts are both arranged to be on the inside of the current path loop formed by the contacts and bushings so that the electromagnetic forces produced by heavy fault current augment the contact pressure. To assist arc extinction, particularly at very low currents, two air dashpots are arranged to direct a puff of air into the arc as the breaker opens. As seen from Fig. 9-16, one arc-runner forms part of the fixed arcing contact assembly, while the other runner

is built into the arc chute itself as seen in Fig. 9-17. This latter illustration also shows the metal splitter plates employed and with this design of circuit-breaker, no magnetic blow-out is required. At the hinged end of the moving contact arm current is transferred to the lower fixed contact block through spring-loaded hinge joints which incorporate annular silver rings on the contact arms to ensure ample conductivity.

The range of high-voltage air-break switchgear developed by A. Reyrolle & Co. Ltd. includes 250 MVA at 3·3/6·6 kV and 500 MVA at 6·6/11/15 kV, the units being of very different physical size. Fig. 9-18 shows a cross-sectional view of a 500 MVA unit.

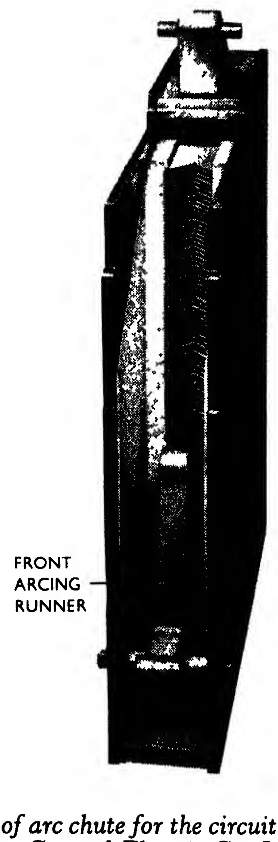


FIG. 9-17.—*Interior view of arc chute for the circuit-breaker shown in Fig. 9-15 (The General Electric Co. Ltd.).*

This illustration gives an excellent indication of the contact system, arc runners and arc chute, the circuit-breaker being shown in the closed position. It will be seen that the hinged moving contact arm has laminated copper flexibles spanning the hinge point. This arm carries at the upper end the main and arcing contact details, the former being silver faced and

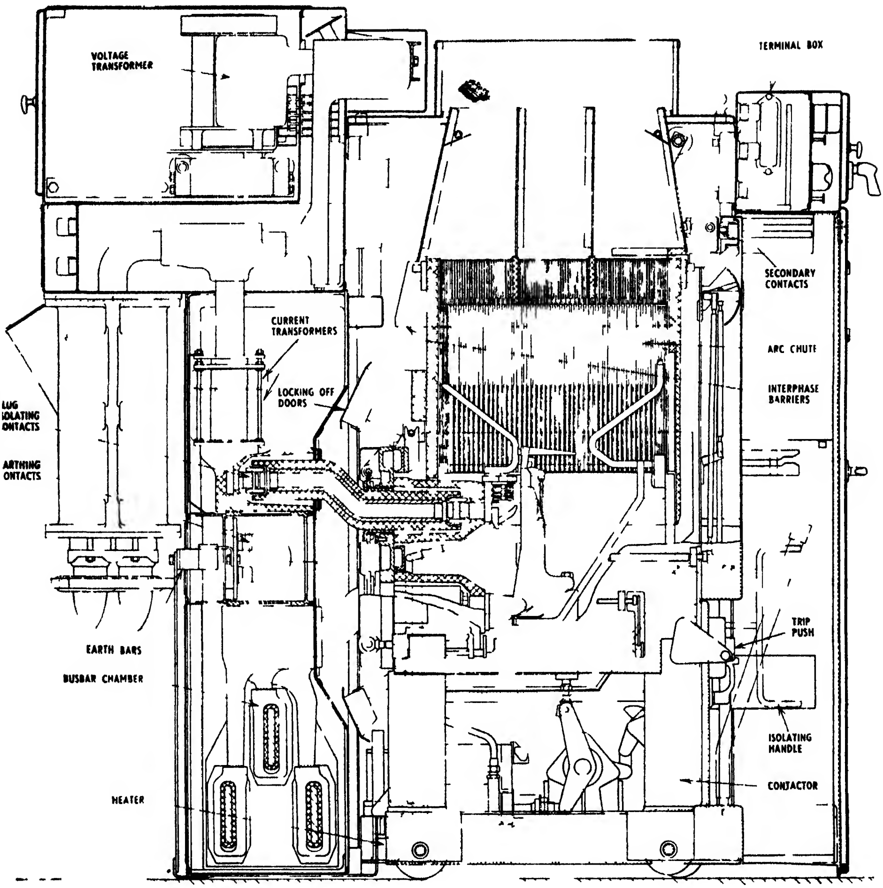


FIG 9-18 - *Section drawing of 6·6/11/15 kV, 500 MVA air-break circuit-breaker (A. Reyrolle & Co. Ltd).*

engaging with multi-finger high-pressure fixed contacts, the arcing contact making a butt type engagement with the fixed arcing contact. Both fixed and moving arc contacts are faced with arc-resisting metal and in order to facilitate the transfer of current from the main contacts to the arcing contacts, and avoid as much as possible any burning of the silver facings on the main contacts, intermediate contacts are fitted, the design of which is similar to the main contacts, but again faced with arc resisting metal.

A study of Fig. 9-18 shows that a tail is attached to the moving contact system and when the breaker opens this tail assists in the function of transferring the arc to the arc runner on the moving contact side. This tail also acts as a shield to prevent the arc from moving down the back edge of the moving contact to a position below the chute.

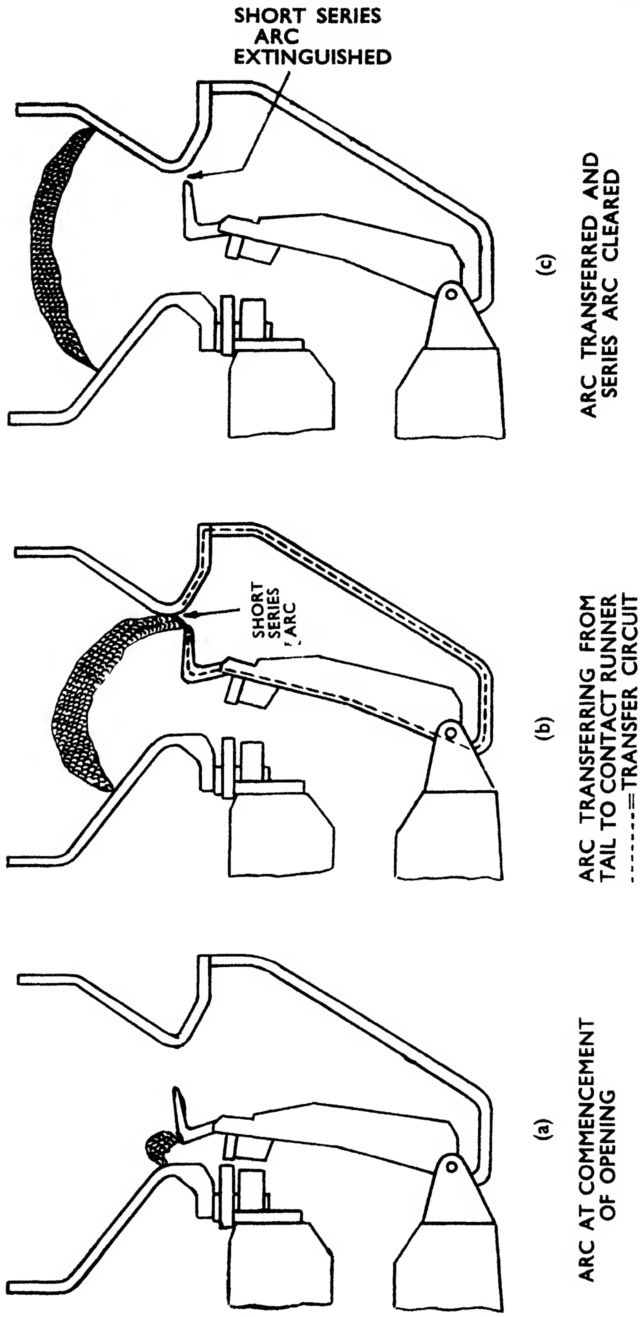


FIG. 9-19.— *Stages in opening of air-break circuit-breaker shown in Fig.* 9-18
(*A. Reyrolle & Co. Ltd.*).

Note also that a link connection exists between the arc runner on the moving contact side and the hinged point of the moving arm, the purpose of this link being to act as a shunt to ensure that, with the breaker open, a short series arc does not persist between the tip of the tail and the runner at a point low down in the arc chute. This point is illustrated in Fig. 9-19.

The arc chutes in this design are of the coil-less type, i.e. coils are not required to energise an external iron circuit to produce a flux to drive the arc into the chute. Instead, sandwich type arc chute plates are employed in which an iron sucker-loop is moulded between plates of refractory material. In addition, the arc chute is so constructed that the arc moves initially in a very restricted tunnel. The slots in the arc chutes are inclined in alternate directions throughout the arc chute and as the arc rises in the chute the slots force the arc column into a zig-zag path of ever increasing length until the top of the slots is reached at which point further bowing of the arc takes place between adjacent arc chute plates beyond the ends of the slots. The zig-zagging of the arc, as described, is illustrated diagrammatically in Fig. 9-20.

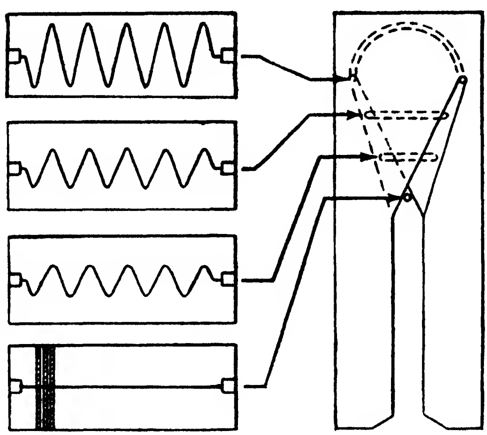


FIG. 9-20.—*Showing how the arc is lengthened in alternately inclined slots in the arc chute* (*A. Reyrolle & Co. Ltd.*

The development of this range of air-break circuit-breakers has been reported recently in an I.E.E. paper (see bibliography) and the principles and theory of the contact system and arc chute designs briefly outlined here are very fully described and discussed in that paper. Fig. 9-21 shows an 11 kV, 500 MVA circuit-breaker withdrawn from its housing and with the arc chutes raised to show the contact system.

A cross-sectional view of a complete air-break switchgear unit as developed by The English Electric Co. Ltd., is noted later in Chapter X (Fig. 10-19), the circuit-breaker in that unit being 6·6 kV 350 MVA rating. The contact system employed in this breaker is shown in more detail in

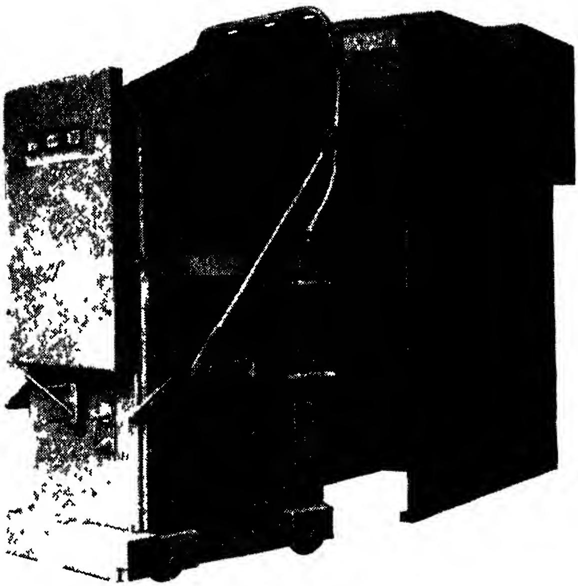


FIG. 9-21.—*11 kV, 500 MVA air-break circuit-breaker withdrawn from its housing and with arc chutes raised. (A Reyrolle & Co. Ltd.).*

Figs. 9-22 and 9-23, and employs main, intermediate and arcing contacts so arranged that on opening, the main contacts open first, quickly followed by the intermediate arcing contacts and then, about fifteen milliseconds later, the arc contacts open This ensures that an adequate gap has been established between the open main contacts by the time the arc contacts part, thus eliminating the possibility of an arc restriking across the main contacts. By suitable design, the arcing, intermediate and main contacts close virtually together when closing a circuit-breaker and thus the main contacts, having pre-loaded high-pressure springs, are up to full pressure a short distance up the first major loop of short-circuit current when the breaker is called upon to close on to a fault.

The arc chute design employs magnetic arc control utilising blow-out coils and magnets to assist in rapid arc extinction Provision is also made to force jets of air on to the arc, primarily for assisting in driving the arc into the chute when the current to be interrupted is relatively low and below that which makes the blow-out coils most effective These puffs of air also scavenge the arc contact gap to prevent restriking.

At the hinge point of the moving contact arm, current is transferred via annular silver rings held in contact by compression springs within the hinge and assisted during short-circuit conditions by the electro-magnetic grip effect of the fault current.

Fig. 9-24 shows the rear of the 6·6 kV circuit-breaker on its withdrawal truck from which will be noted the arc chute structures and above them the exhaust vents.

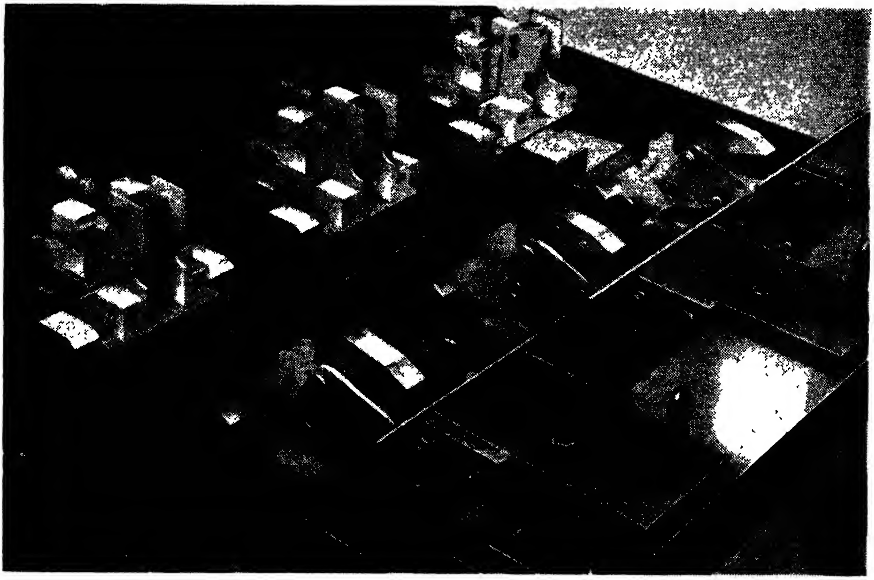


FIG. 9-22.—*Contact system in open position with arc chutes removed. (The English Electric Co. Ltd.).*

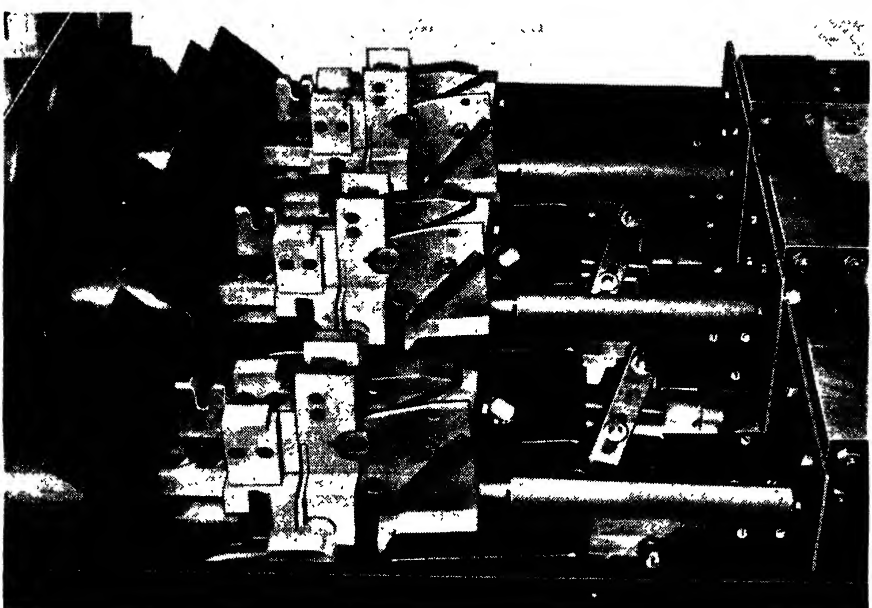


FIG. 9-23.—*Contact system in closed position, with arc chutes removed. (The English Electric Co. Ltd.).*

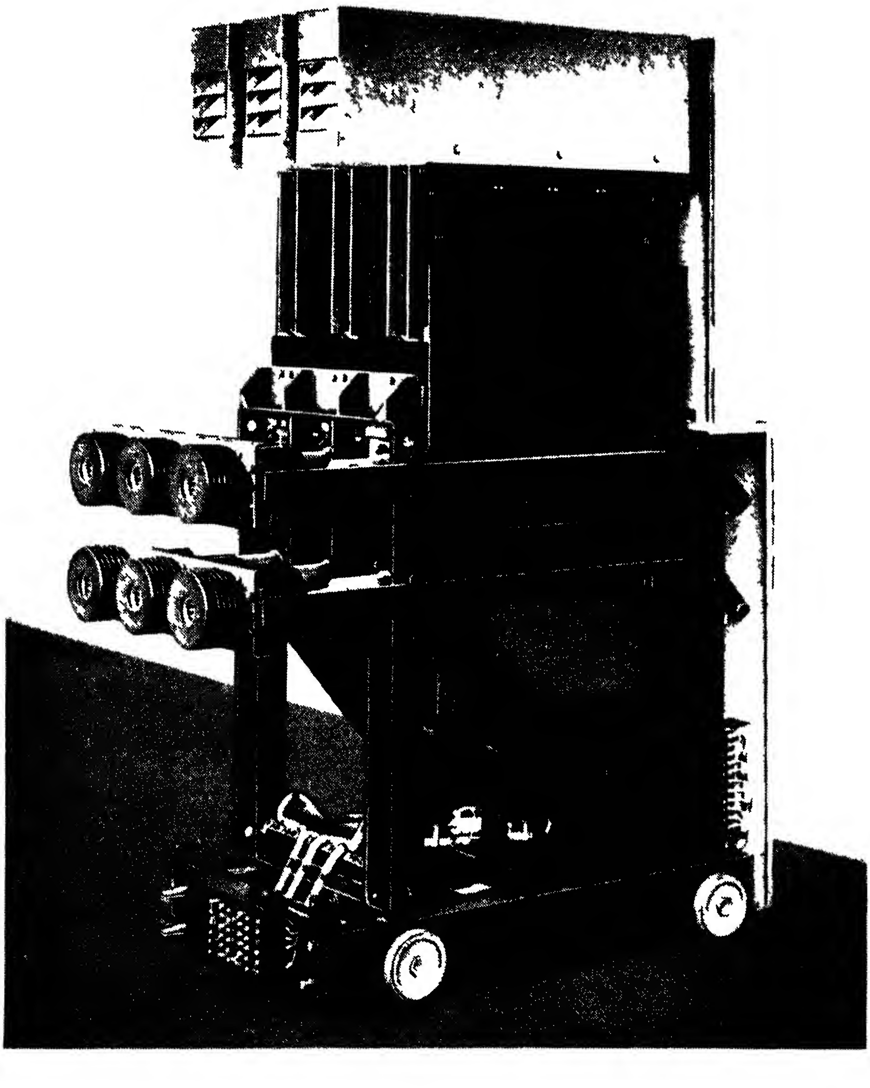


FIG 9-24.—*Rear view of 6·6 kV, 350 MVA air-break circuit-breaker on truck withdrawn from housing (The English Electric Co Ltd).*

The range of air-break circuit-breaker designs of The English Electric Co cover voltages of 3·3 to 11 kV, with breaking capacities of 150 MVA to 500 MVA

BIBLIOGRAPHY

"*Fundamentals of A.C. Circuit-Interruption,*" Dr. Erwin Salzer (Allis-Chalmers Manufacturing Co.).

"Oil-Less Metalclad Switchgear for Medium Voltage Alternating Current Circuits up to 660 Volts," H. E. Cox and L. Drucquer, "Journal I.E.E.," Vol. 87, No. 527, p.461, Nov., 1940.

"New Developments in Air-Break Circuit-Breakers," A. R. Blandford, "English Electric Journal," April, 1940.

"Development of High-Voltage Air-Break Circuit-Breakers with Insulated Steel-Plate Arc Chutes," F. S. Fay, J. A. Thomas, D. Legg and J. S. Morton, "Proceedings I.E.E.," Paper No. 2746S, Part A, No. 29, Vol. 106, October, 1959.

"Switchgear Trends in British Stations," R. P. E. Tabb and S. E. Newman, "Electrical Times", 21st June, 1962.

CHAPTER X

HIGH-VOLTAGE A.C. INDOOR SWITCHGEAR

CHAPTER X

HIGH-VOLTAGE A.C. INDOOR SWITCHGEAR

High-voltage switchgear for use indoors usually takes one of the following forms:

(*a*) The air-insulated stationary cubicle type, in which all the component items occupy fixed positions.

(*b*) The air-insulated truck type, in which certain component items are carried on a movable carriage.

(*c*) The compound-filled type, which is often not very different from designs under (*b*) but has the busbars and certain connections immersed in compound and the instrument current transformers immersed either in compound or oil.

(*d*) Fuse-switch and ring main units.

Each of the types outlined has advantages and disadvantages. For example, in (*a*) and (*b*) *all* the component items are easy of access, whereas in (*c*) the immersion of certain items may make access difficult.

On the other hand, filling of busbar and other chambers in type (*c*) makes for greater operational reliability, reducing the possibilities of flashover despite smaller electrical clearances. As to cost, this is roughly in the order (*a*), (*b*), (*c*), with (*a*) the lowest, although this may not always be so, particularly if elaborate interlocks are required.

(*a*) AIR-INSULATED STATIONARY CUBICLES

At one time the most popular form of stationary cubicle was that in which the housing for the component apparatus was built of moulded stone slabs. This type, shown typically in Fig. 10-1, has the advantage of giving maximum access to the apparatus, but it takes up considerable space in all directions and cannot be factory assembled. Usual practice is for the slabs to be pre-cast, all holes necessary for the support of apparatus being cored in the slabs. Considerable accuracy is necessary in this process as errors are not easy to rectify. Assembly of the slabs on site is a specialist's job, and breakage of slabs means delay in obtaining replacements.

The concrete mixture used for this type of housing should be strong enough for its purpose without reinforcement, and should comply with B.S. 268.

Phase separation is usually arranged throughout and the stone walls are regarded as being at earth potential, full clearances being maintained accordingly. In order to obtain phase separation in the isolator chambers, the isolating switches are of the single pole type arranged for hand operation by means of an insulated rod.

Today, stone cubicles rarely find favour if only because of the space they occupy. If switchgear of the stationary type is preferred, it is usual

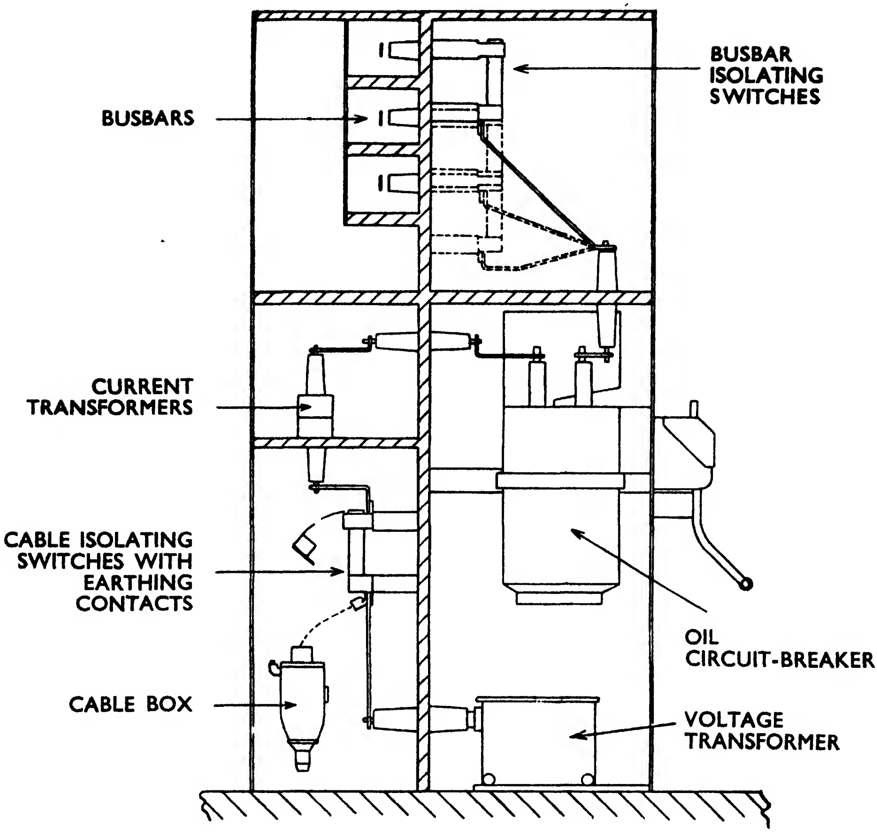


FIG. 10-1.—*Stonework cell, single busbar.*

to install a sheet steel type based on a bolted or welded structure, an example being shown in Fig. 10-2. Doors to give access to the apparatus may be arranged either at the back or the front or both, double access being preferable as it allows easier maintenance and a better disposition of the apparatus. Each cubicle in the switchboard is self-contained.

In Fig. 10-2 no isolating switches are included on the cable side of the oil circuit-breaker. In many instances (see Chapter XIII) these are necessary and it is easy to see that to introduce them involves complication.

In its simplest form, no interlocks are provided between the circuit-breaker and the isolating devices or between these and the cubicle doors. Such gear is a very real danger except in the hands of highly skilled technicians with a full appreciation of the risks involved. To eliminate the danger means a complicated and expensive system of mechanical or electrical interlocks. Mechanical interlocks are not difficult to defeat and may therefore give a false sense of security, while electrical interlocks require a separate source of supply.

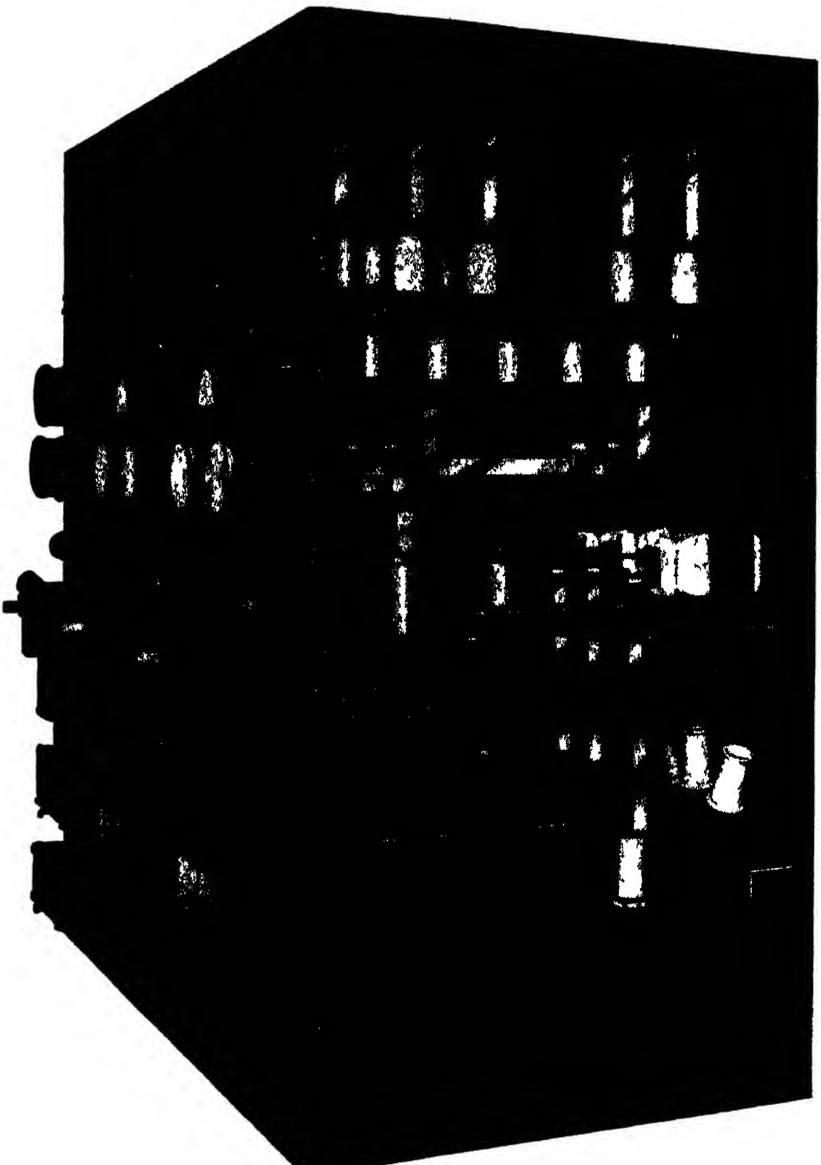


Fig. 10-2.—*Steel cubicle type switchboard with duplicate busbars and off-load selectors.*

In general, fixed cubicle types of gear are limited to 11 kV—or 33 kV in special circumstances—while it is not usual to contemplate breaking capacities in excess of 500 MVA, owing to the very large housing which would be necessary and to other difficulties.

Because of the many disadvantages outlined, and the relatively few advantages, the inclusion of these types in this chapter may be regarded as of historical interest, as present tendencies are towards the use of other types

(*b*) AIR-INSULATED TRUCK TYPES

As indicated earlier, this is a type in which certain component items are mounted on a carriage which can be moved, and, in so doing, perform the function of isolating those components and at the same time making them accessible for inspection and maintenance. This principle is, of course, applied also in some of the gear to be described later under (*c*), but here we are concerned with gear which is of the air-insulated type.

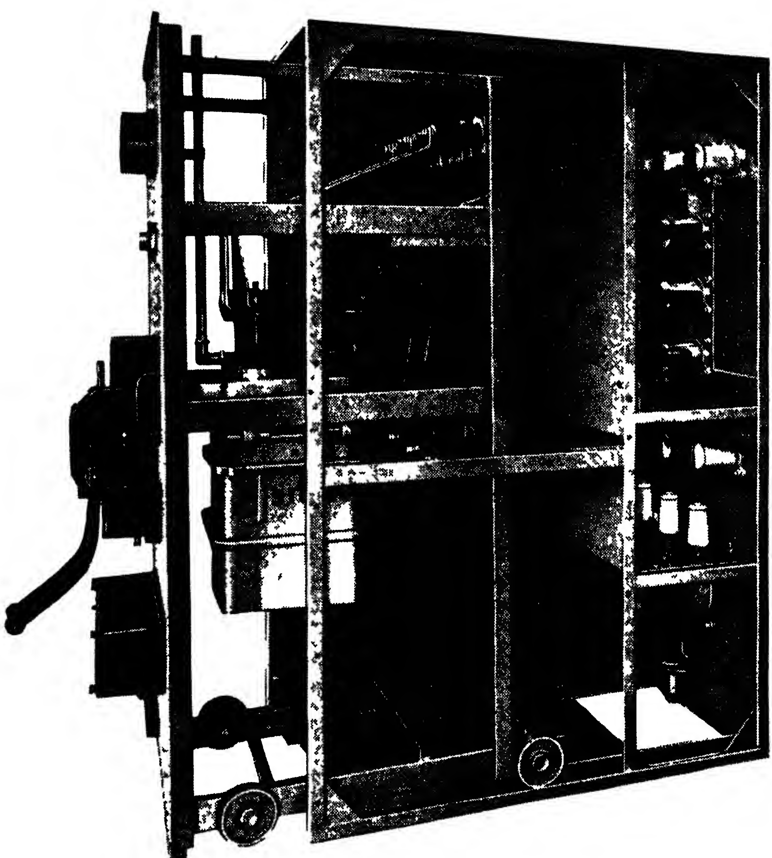


FIG. 10-3 —*Draw-out truck type metalclad gear with end covers removed*

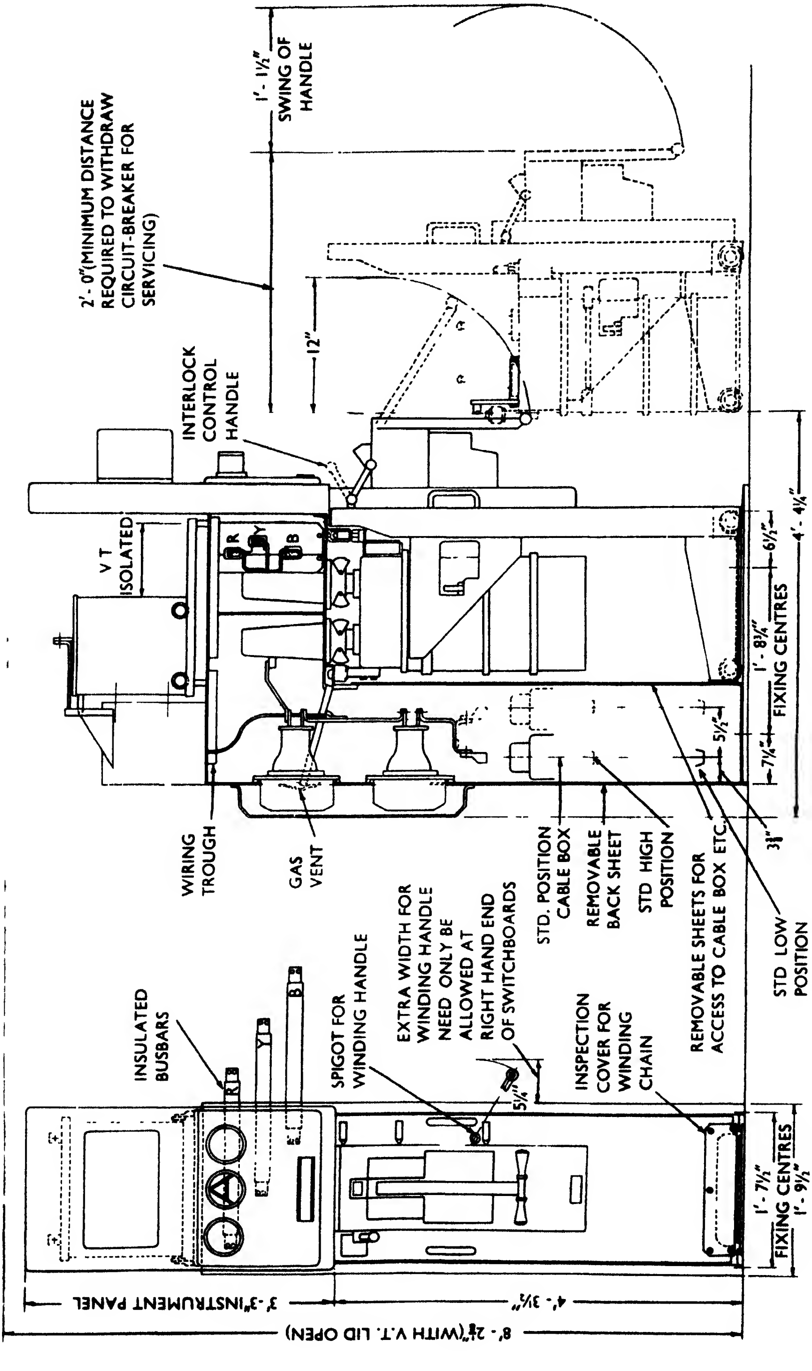


FIG. 10-4.—*Typical vertical isolation unit with air-insulated busbars (Johnson & Phillips Ltd.).*

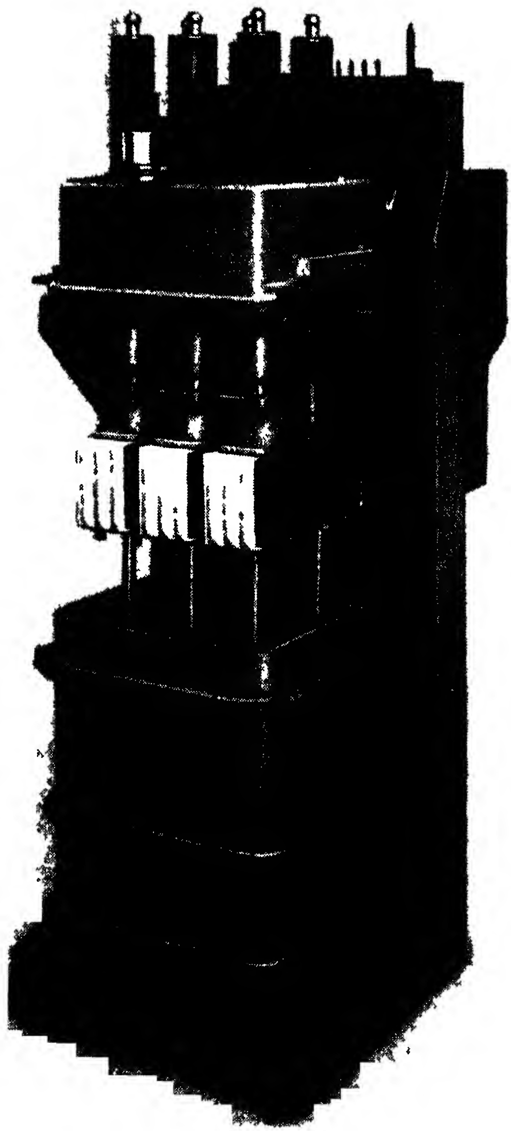


FIG. 10-5.—*Circuit-breaker raised from its oil tank for contact inspection (Johnson & Phillips Ltd.).*

Probably the earliest form of withdrawable switchgear was that which first introduced the designation "truck type". An example of this type is shown in Fig. 10-3, and it is interesting to recall that original designs were built some forty years ago. Its popularity was due to the fact that, with the carriage withdrawn, particularly easy access is given to the major items of apparatus, i.e., the circuit-breaker, current and voltage transformers, isolating finger contacts, panel wiring, etc.

In the withdrawn position, full isolation is automatically provided, the isolators comprising a system of self-aligning wedge and finger contacts of the line pressure type. Mechanical interlocking ensures that the moving carriage can only be withdrawn or replaced with the circuit-breaker open, there being no danger of breaking load current on the isolating devices. Secondary connections from current and voltage transformers are also isolated at auxiliary plug and socket contacts on withdrawal of the carriage.

Automatic shutters are provided in the fixed housing which, with the carriage withdrawn, cover the orifices through which the moving portion of the isolators pass. This ensures that inadvertent contact with live parts is avoided, and either or both sets of shutters can be locked when closed to prevent access by unauthorised or uninformed personnel. The shutters are in the open position in Fig. 10-3 and the roller mechanism for operating them is carried at the top of the moving structure.

On circuits where it is necessary to include a voltage transformer, this would be carried on the wheeled base of the truck and would thus be withdrawn and isolated along with the circuit-breaker.

This type of unit requires fairly considerable space in front in order to fully withdraw the carriage and, on occasion, remove it completely and for this and other reasons, the modern version, while retaining the principle of a moving carriage, is arranged so that the function of isolating is by vertical movement, i.e. the circuit-breaker is lowered* to floor level. In most cases this is all that will be required but for maintenance purposes, the lowered circuit-breaker can then be wheeled forward, all as shown in Fig. 10-4. With the breaker thus removed, it is possible (a) to raise the circuit-breaker clear of the oil tank for examination, maintenance or contact replacement as shown in Fig. 10-5 or (b) fit a portable one-piece earthing device as shown in Fig. 10-6 for the purpose of earthing the cable prior to working on it.

In this design, the moving carriage carries only the circuit-breaker, the instrument transformers, instruments, relays and other components being mounted on or in the fixed housing.

Raising or lowering of the circuit-breaker may be achieved by various means, some designs employing a jacking arrangement while in others two jack screws are operated by a handle at the front of the unit, the circuit-breaker being supported on two side arms and riding up or down on runners.

As in the original truck type of gear, shutters automatically cover the fixed isolating contacts when the carriage is lowered and both shutters (busbar and cable) can be locked closed independently as may be required. When cable earthing is being undertaken, only the busbar shutter would be locked closed as the earthing plugs must enter the sockets on the cable side. A typical set of shutters is shown in Fig. 10-7.

**As we shall note later, one version functions to raise the circuit-breaker.*

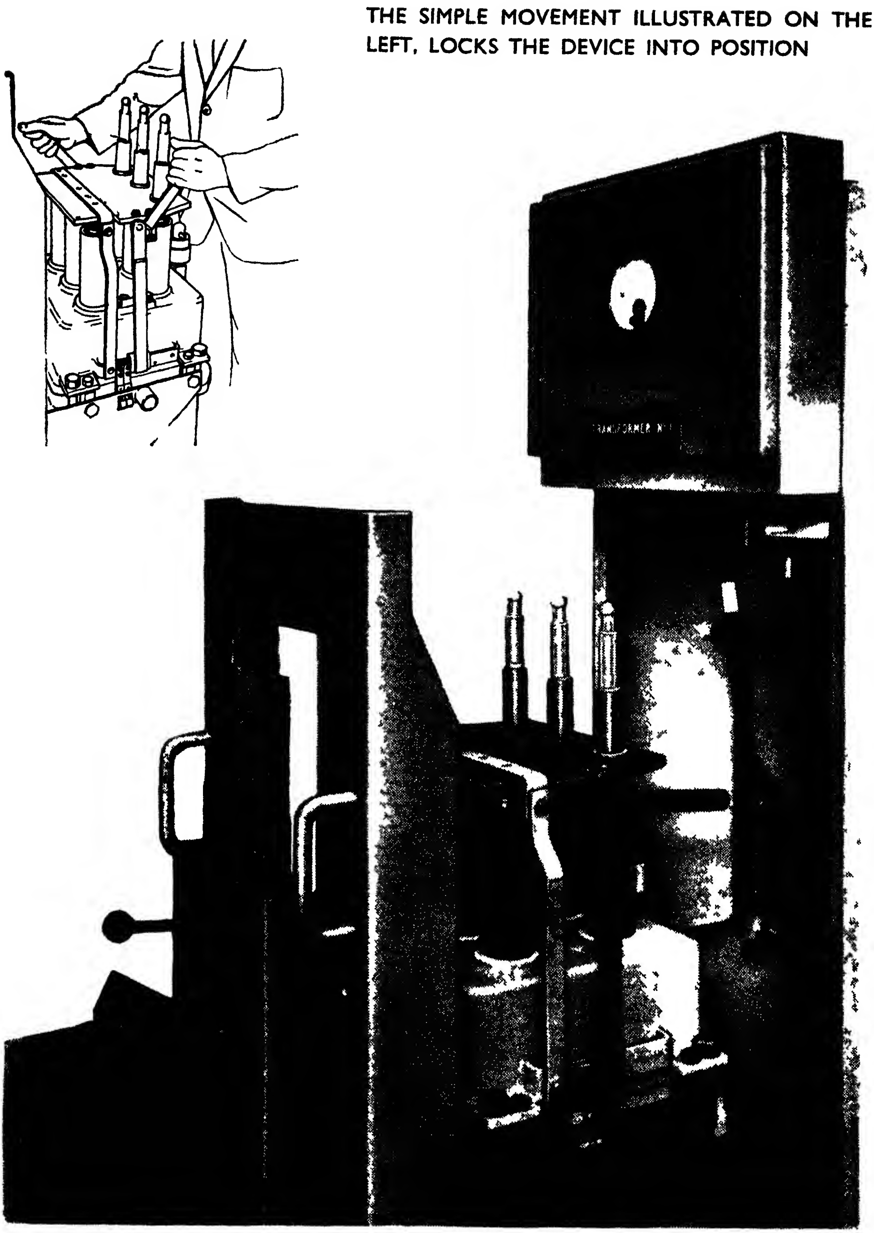


FIG. 10-6 –*Circuit-breaker fitted with a portable one-piece earthing device (Johnson & Phillips Ltd.)*

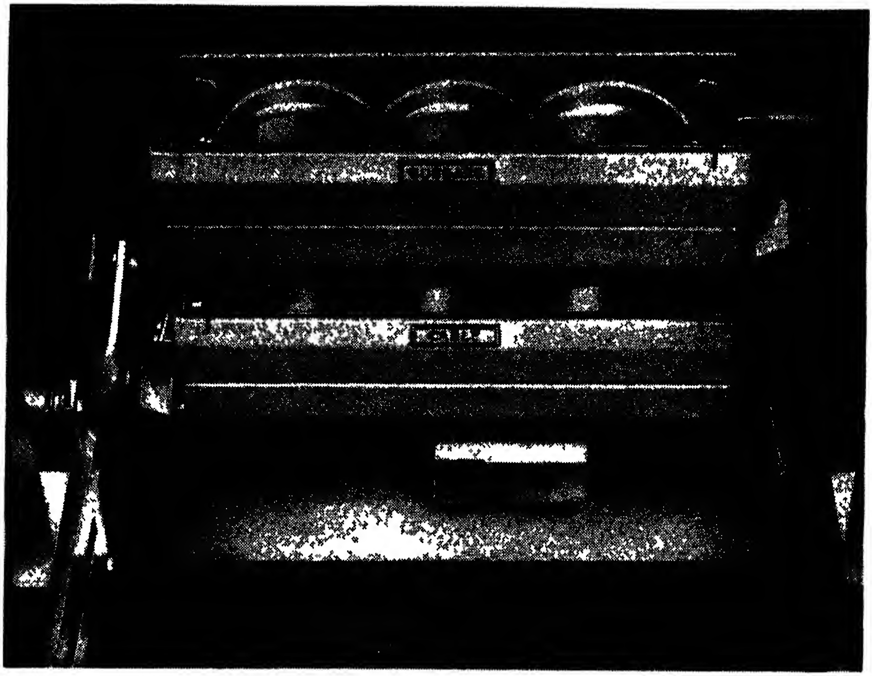


FIG. 10-7.—*Busbar and cable isolating spout shutters, showing the position of the padlocks (Johnson & Phillips Ltd).*

A simple one-piece device enables the cables or busbars to be earthed through the circuit-breaker. This device is attached to the isolated terminals of the breaker by means of plugged contacts, and is drawn down to full contact position by side handle levers onto the breaker frame. The circuit-breaker is then raised to the earthing position and when closed earths the required circuit.

It is obviously necessary when isolating the primary circuit by lowering the circuit-breaker carriage, to similarly isolate all secondary circuits to instruments, relays, etc. and for this purpose, secondary plugs and sockets are carried on the moving and fixed elements of the unit. Those used in the unit described are shown in Figs. 10-8 and 10-9, the latter illustration also showing how access is obtained to the rear of the instrument or relay panel.

In this design, current transformers are accommodated in the main fixed housing immediately above the cable boxes (see Fig. 10-4) while if a voltage transformer is required, this is mounted on top of the fixed housing and is separately withdrawable on rails. This transformer can be withdrawn without need to interrupt the primary circuit but when withdrawn, automatic shutters cover the isolating orifices for safety. A further interlock ensures that access to the interior of the transformer tank is only possible

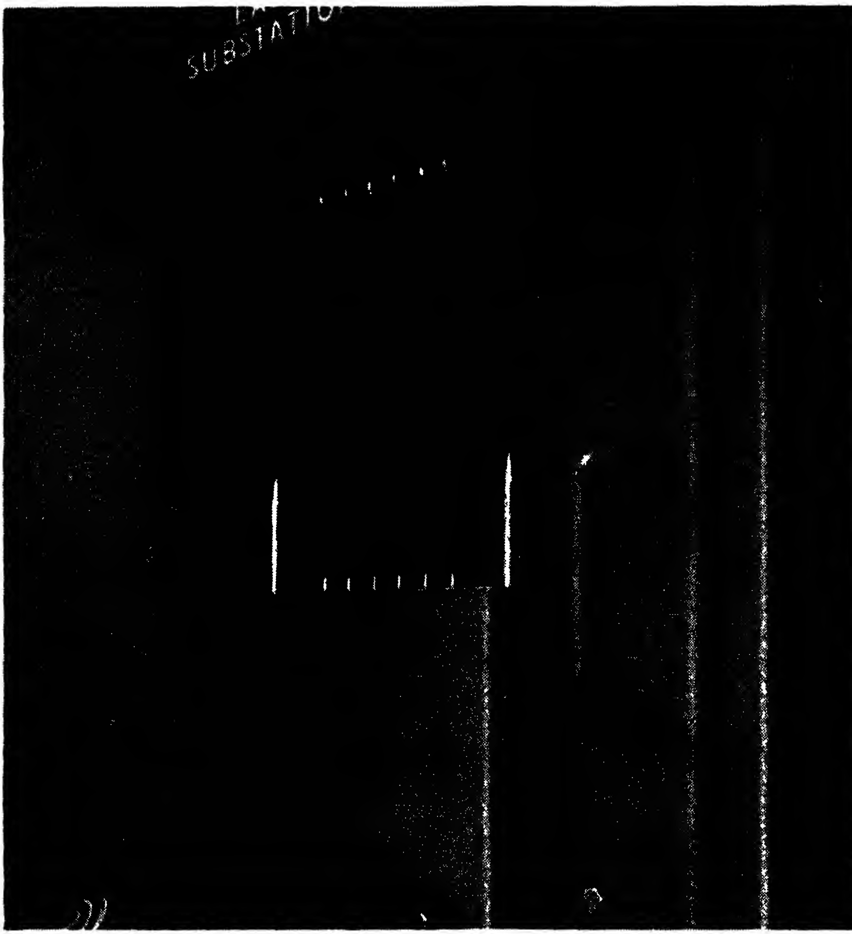


FIG. 10-8.—*Secondary plugs and sockets in isolated position (Johnson & Phillips Ltd.).*

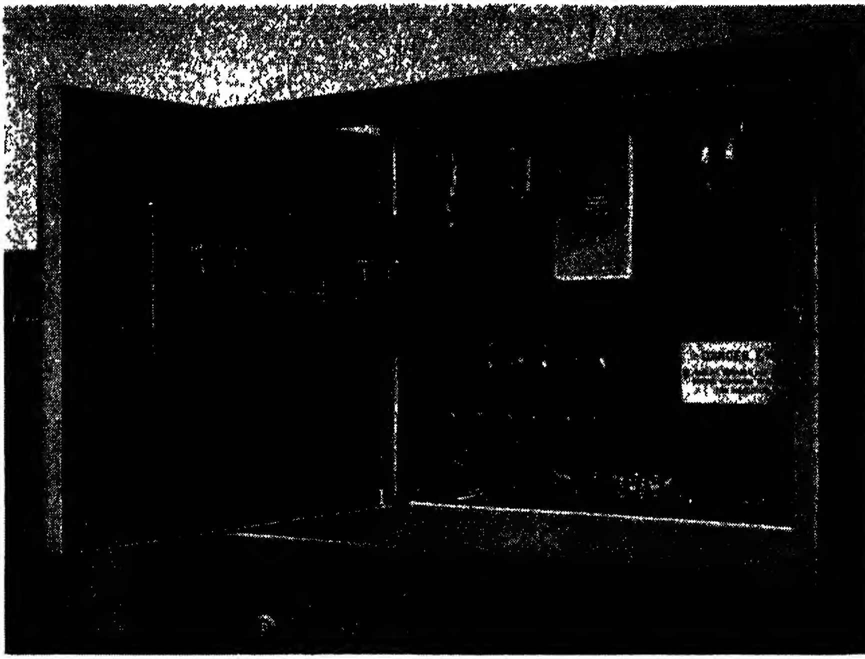


FIG. 10-9.—*A typical method of wiring for instrument panels. The busbar inspection cover shown on the right at the back of the panel can be removed (Johnson & Phillips Ltd.).*

in the withdrawn position. Such access is necessary if primary fuse replacement is required as these fuses are below oil level in the transformer tank.

The unit shown in Fig. 10-4 is of the single busbar type but can be arranged for duplicate busbars when required. The method used is that of transferring the circuit-breaker as discussed later in Chapter XIII and illustrated diagrammatically in Fig. 13-21. A switchboard having a duplicate busbar system is shown in Fig. 10-10 and here it will be noted that the four units on the left centre show the moving carriage within the fixed housing to a greater depth than in the remaining units. This illustrates that certain units are plugged-in to one (rear) set of busbars and others in the forward position are plugged-in to the other (front) set of busbars.

We shall also note in Chapter XIII, Fig. 13-2, how certain precautions may be taken against fire risks by accommodating a bus sectionalising unit within fire dividing walls. Such an arrangement is illustrated in Fig. 10-11 where two section switches are employed and each is housed in its own brick cell.

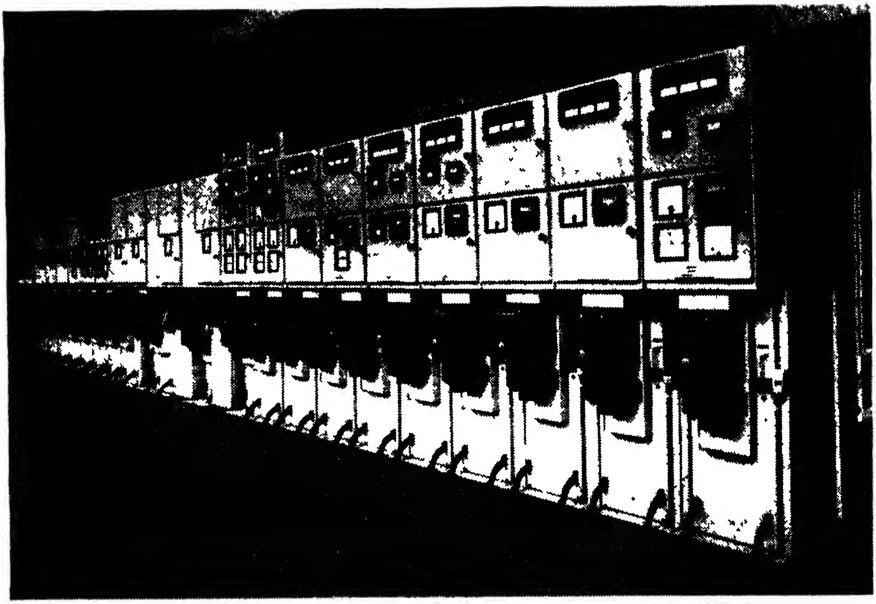


FIG. 10-10.—*Switchboard of vertical isolation units with duplicate busbars (Johnson & Phillips Ltd. and by courtesy of the National Coal Board).*

In the type of gear under review, as with other types yet to be noted, interlocking for safety is an important feature and, as opposed to the fixed stone or steel cubicle types, such interlocking is achieved relatively easily. The interlocks normally provided are:

(1) The circuit-breaker must be in the open position before it can be lowered on its carriage to isolate.

(2) Conversely, it must not be possible to raise the circuit-breaker into the plugged-in position with its contacts closed.

(3) The circuit-breaker cannot be plugged-in unless its oil tank is correctly secured to the top plate.

(4) Closing of the circuit-breaker must only be possible in the fully plugged-in or fully isolated positions or, when fitted with means for earthing either the cable or the busbars, in the correct location for this function.

In the designs so far illustrated, the circuit-breaker operating mechanism is clearly visible at all times. In other designs, of which Fig. 10-12 is an example, the complete moving carriage with the circuit-breaker operating mechanism is normally "masked" from view by a door which has an observation window for an on-off indicator.

FIG. 10-11.—*22-panel switchboard composed of vertical isolation units and including two bus section switches within fire walls (Johnson & Phillips Ltd. and by courtesy of the B.T.C. British Railways).*

In passing it is of interest to note that much of the insulation used in the unit shown in Fig. 10-12 is of epoxy resin. This applies to the circuit-breaker bushings, busbars, and the current transformers, the latter being encapsulated in the material. The problems associated with casting in epoxy resins of bushings etc. are noted in an I.E.E. paper No. 2835 S (see bibliography) and later in this chapter we shall note in particular an example where a cranked rotatable bushing is used, cast in epoxy resin.

In the design shown in Fig. 10-12, and in that in Fig. 10-13, the secondary connections between the fixed and moving positions are carried in a flexible tube terminating in plug and socket contacts.

It has been noted on page 279 that in one design of vertical isolation, the circuit-breaker is raised to isolate the circuit instead of being lowered. This is known as "inverted vertical isolation" and the principle is used in a range which includes both indoor and outdoor types. An outdoor unit is shown in cross-section in Fig. 10-14 from which it is seen that in the normal

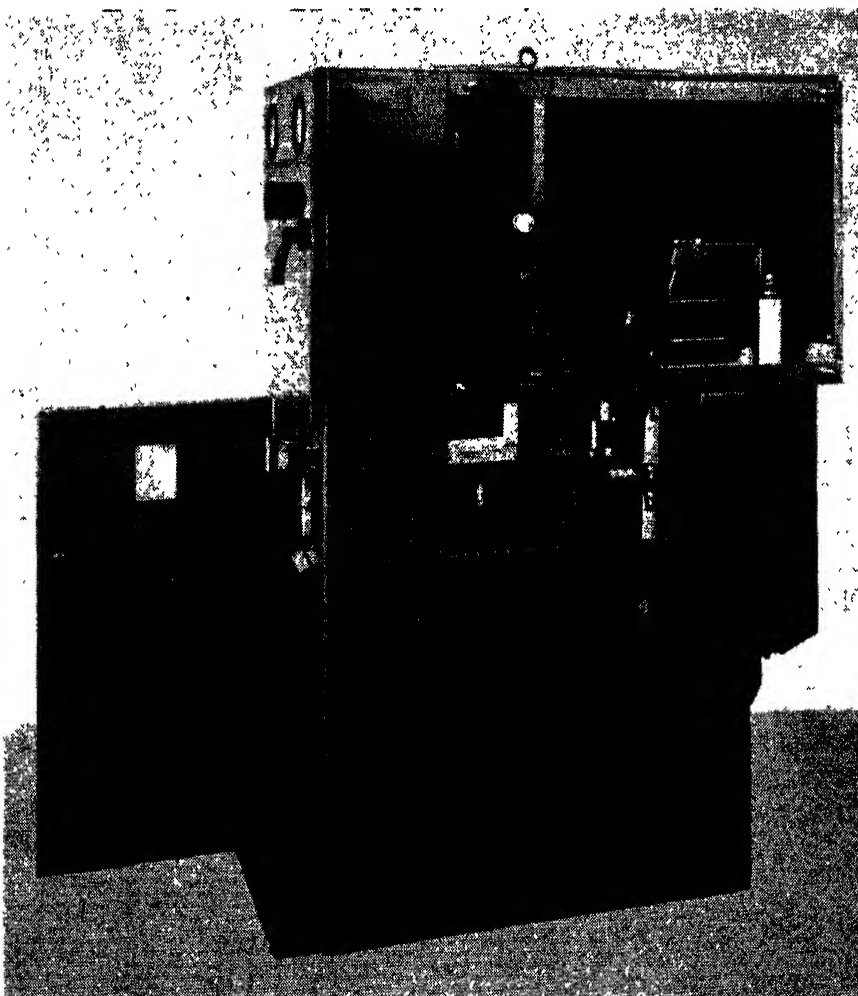


FIG. 10-12.—*Vertical isolation unit with side panels removed showing fully insulated busbars etc., and with the front door open (The General Electric Co. Ltd.).*

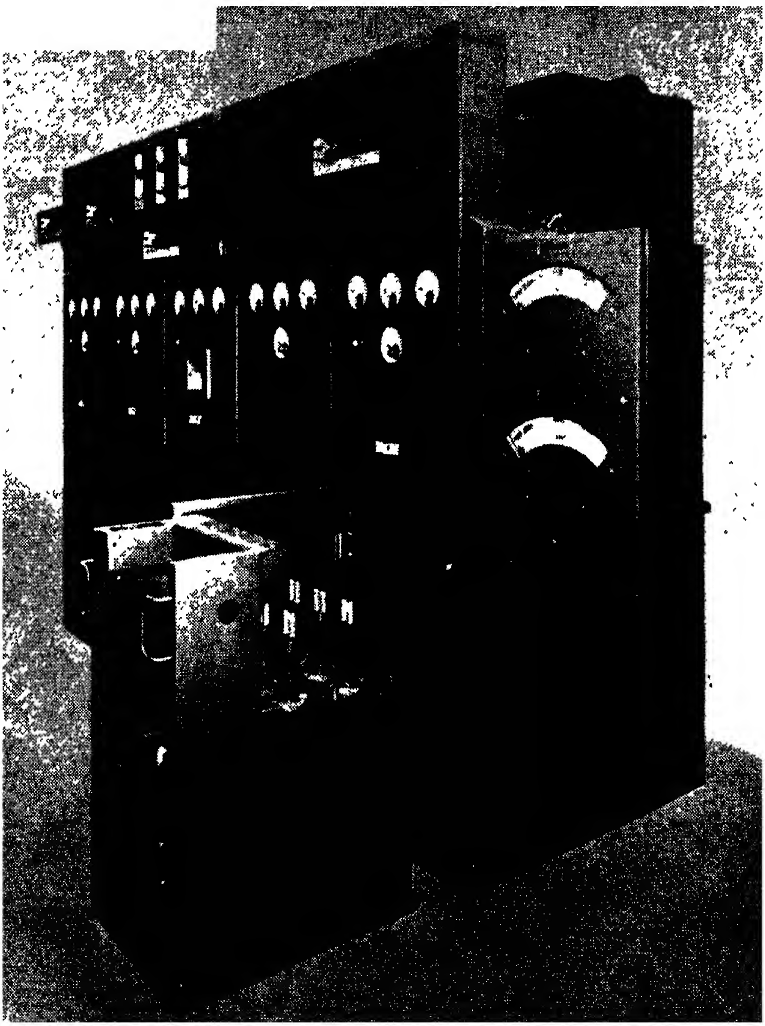


FIG. 10-13.—*Switchboard of vertical isolation units (The General Electric Co. Ltd.).*

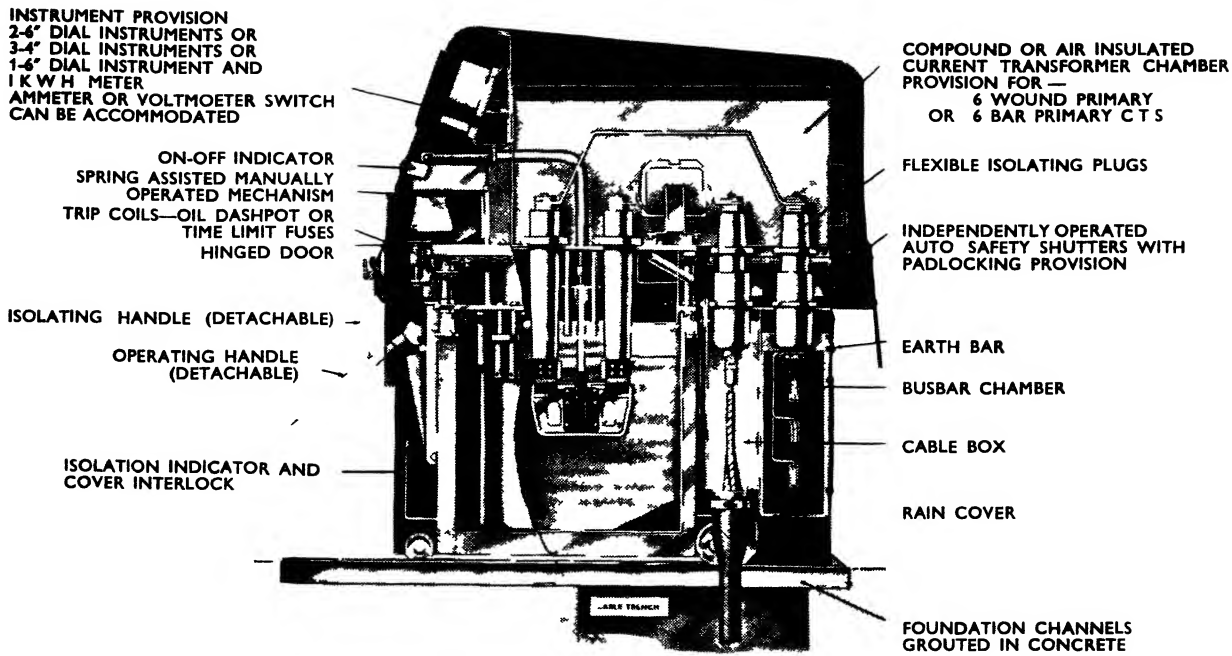


FIG 10-14—*Cross-sectional view of an inverted vertical isolation unit for outdoor service (Yorkshire Switchgear and Engineering Co Ltd)*

service position the circuit-breaker is at near-ground level with the cable and busbar isolating plugs and sockets immediately behind. In this position, the elevating screws hold the circuit-breaker firm against the base of the carriage at floor level, thereby reducing the stress on the tank bolts and on the isolating plug system due to the shock of operation during short-circuit clearance. To isolate, the circuit-breaker, along with the upper chamber housing current and voltage transformers, is raised vertically by means of the elevating screws which are operated from an external (detachable) handle. In the isolated position, the moving portion can be drawn forward from the cable and busbar components in the fixed portion, as shown in Fig. 10-15.

FIG. 10-15—*Outdoor type inverted vertical isolation unit in raised and withdrawn position Also seen is a load-breaking fault-making oil switch in its raised (isolated) position (Yorkshire Switchgear and Engineering Co. Ltd.).*

Safety shutters automatically cover the cable and busbar orifices with the unit in this position.

In the indoor version no change in principle is involved but the weatherproof hood is omitted and the instrument and relay panel is external, as shown in Fig. 10-16, an illustration which shows clearly the circuit-breaker at floor level in the service position.

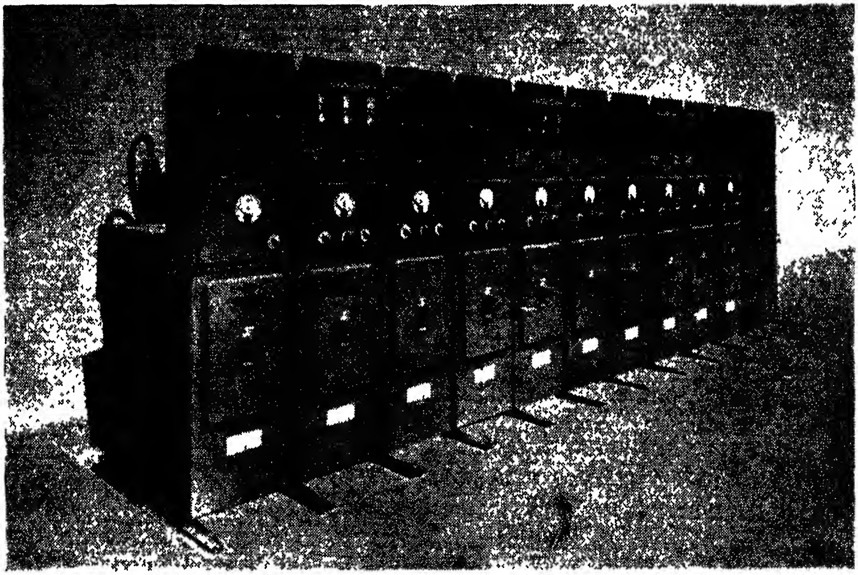


FIG. 10-16.—*Indoor type switchboard of inverted vertical isolation units (Yorkshire Switchgear and Engineering Co. Ltd.).*

The outdoor version of this design will be noted in further detail in Chapter XVIII.

So far the units illustrated and discussed have been those in which oil circuit-breakers are used but in Chapter IX we have noted the existence of a number of air-break circuit-breakers in the voltage range 3 300 to 11 000 volts. Much of the development in this direction has been associated with gear for the control of plant and distribution systems where concentration of power is high, such as for power station auxiliaries and steel works supplies. The normal current ratings for this class of gear are of the order 1 200/3 000 amperes and this, coupled with the naturally large arc chute system for these relatively high voltages (in terms of air-break) leads to switchgear units which are much larger than those noted earlier.

The principle of horizontal isolation and withdrawal has been maintained in these designs and externally at least one design is not dissimilar in appearance to its counterpart utilising an oil circuit-breaker. This is a design by The General Electric Co. Ltd. and a typical switchboard of 3 300 volt units shown in Fig. 10-17 can be compared with an earlier illustration Fig. 10-13.

A cross-sectional view of a complete unit is shown in Fig. 10-18 from which it will be seen that two integral earthing switches are included in the design, one for earthing the outgoing cable, the other for earthing the busbars, and each individually operated by handles accessible only when the truck is partially withdrawn. Earthing is completed through the circuit-breaker.

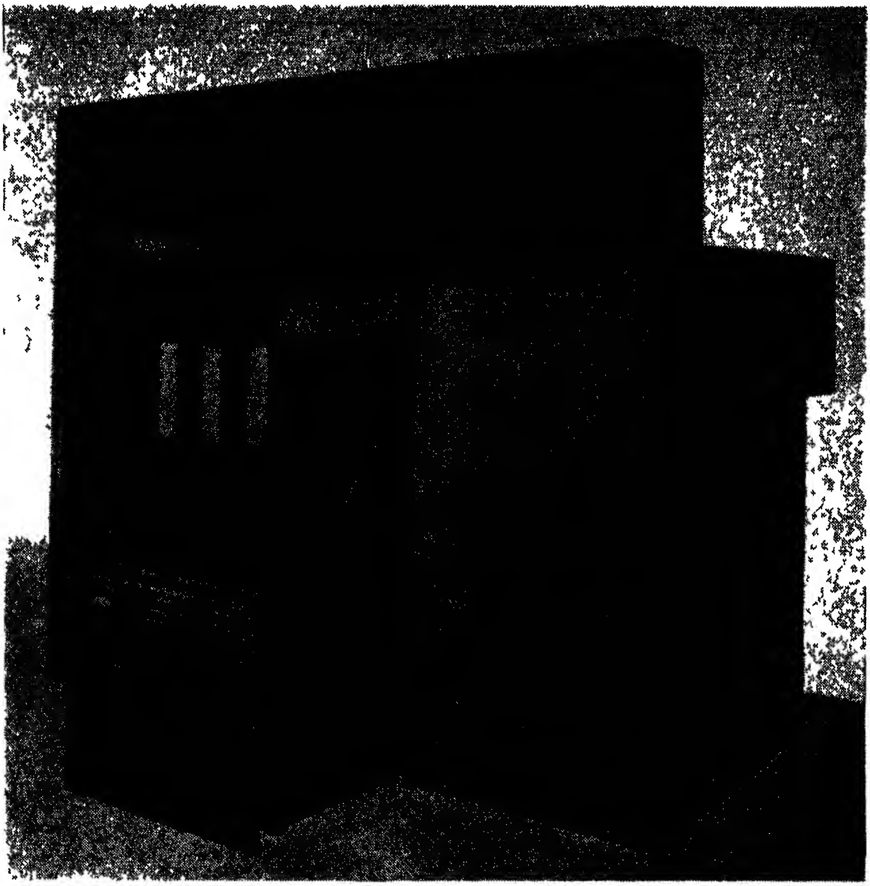


FIG 10-17—*Horizontal draw-out switchboard 3·3 kV employing air-break circuit-breakers One breaker partly withdrawn with door open (The General Electric Co. Ltd.).*

In this design, unlike those noted earlier where oil circuit-breakers are employed, it is not necessary to move the breaker carriage to isolate. Instead this function is performed by means of retractable contact assemblies which slide into and out of contact with the fixed busbar and feeder connections in the housing. These contacts can be seen in Fig. 10-18 in the separate compartment immediately above the air-insulated busbar chamber and operation is by means of an external handle. Interlocks ensure that one or other of the earthing switches can only be closed if the associated set of

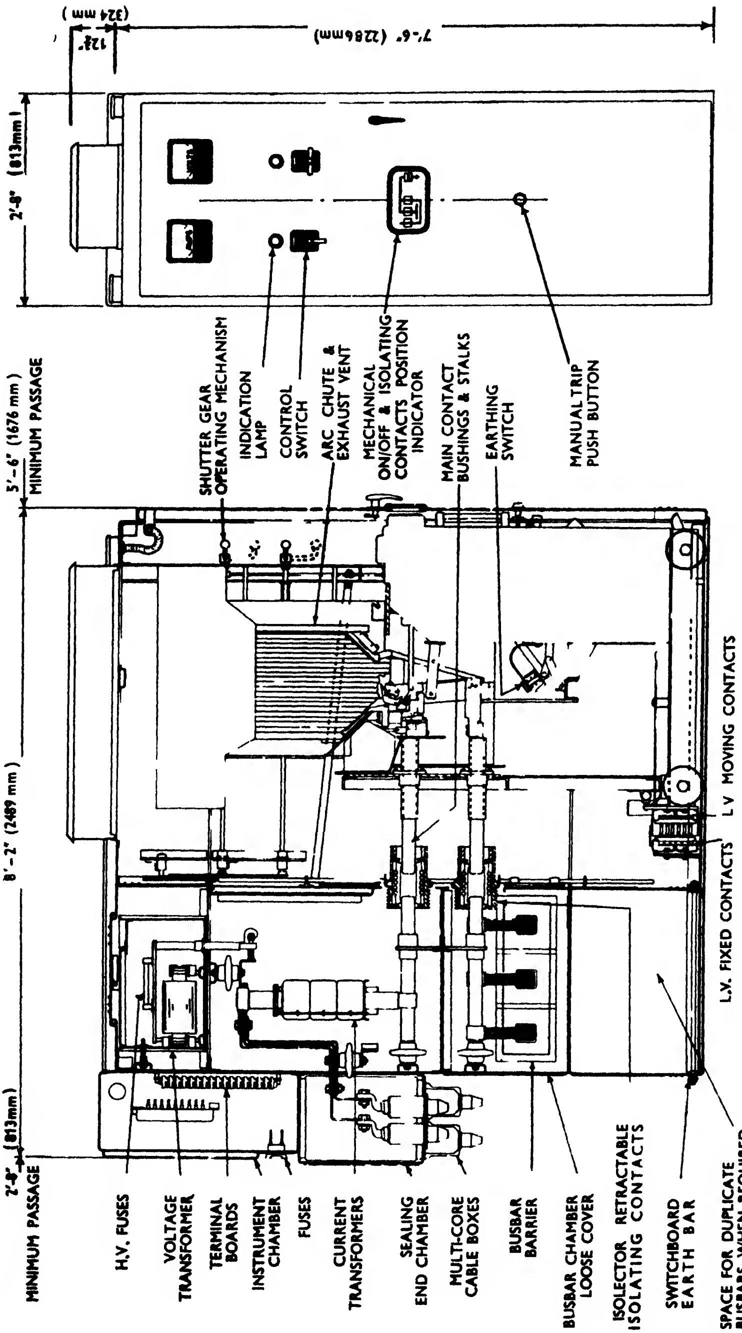


FIG 10-19 —*Cross-sectional view of 11 kV air-break switchgear unit (The English Electric Co Ltd)*

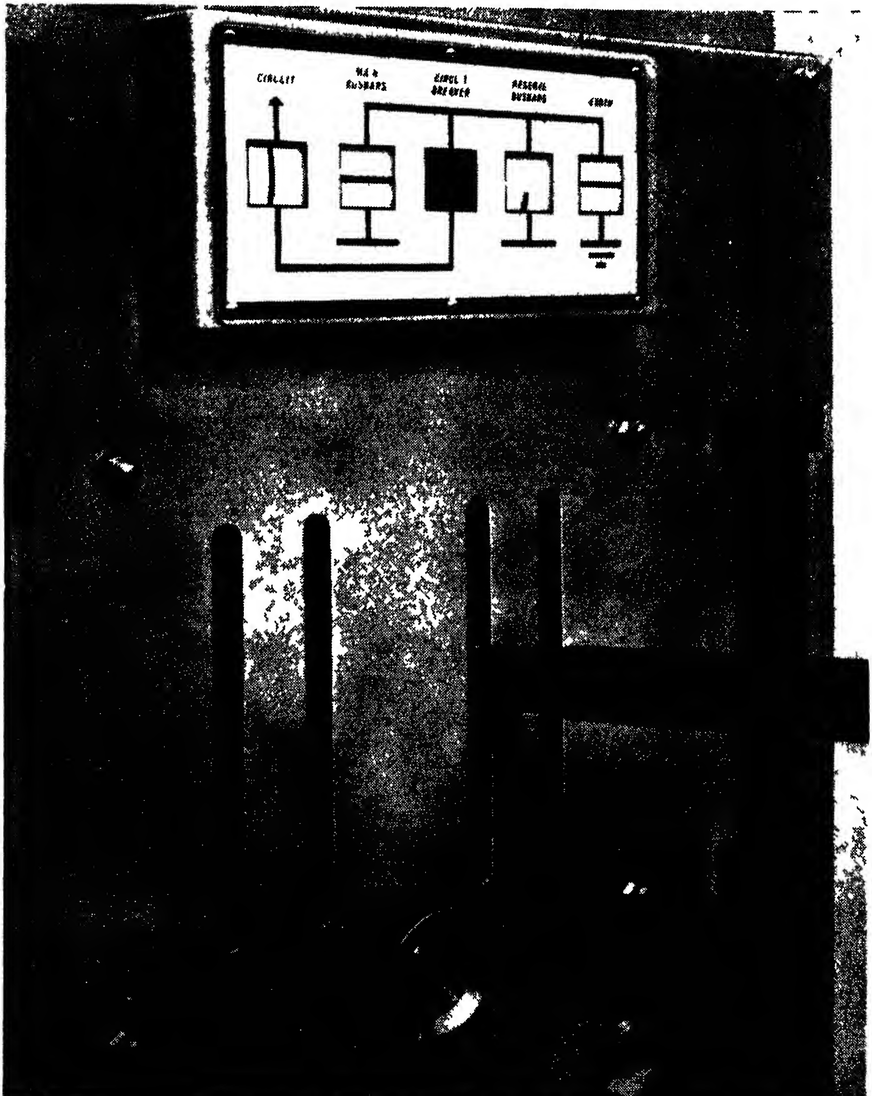


FIG 10-20 —*View of interlock gate on a double-busbar unit showing operating lever inserted and isolating the reserve busbars* (*The English Electric Co Ltd*)

isolating contacts is in the fully retracted position and closing of an earth switch automatically locks them in this position but permitting the other set to be closed

The English Electric range of units employing h.v. air-break circuit-breakers includes 3·3, 6·6 and 11 kV. A design for 11 kV is shown in Fig. 10-19.

Here again the circuit-breaker can be isolated without withdrawal of the breaker carriage, two banks of three retractable bridge contacts being arranged to slide horizontally to join or disconnect the breaker and the fixed elements in the housing. These contacts, given the trade name of "Isolectors",* are operated through an interlocked gate at the front of the unit by a removable handle, each set being capable of individual operation as required in conjunction with the appropriate earthing switch. This interlocked gate, shown in Fig. 10-20, requires only that the operator should select the operation required, insert the handle in the appropriate position and complete the operation. The rotatable trip knob in this illustration must be pushed in and rotated initially to ensure that the circuit-breaker is tripped and cannot be closed until the selected operation is completed. When rotated, this knob operates an interlocking plate which slides to uncover the socket of the facility required, all other sockets being covered. Above the gate is a mechanically operated position indicator in the form of a mimic diagram to show the state of the circuit at any time.

The retractable contacts in this design are seen clearly in Fig 10-19 and in more detail in Figs. 10-21 and 10-22. When arranged for duplicate busbars, a further set of "Isolector" contacts is necessary and the choice of busbar to which the circuit is connected is made at the gate.

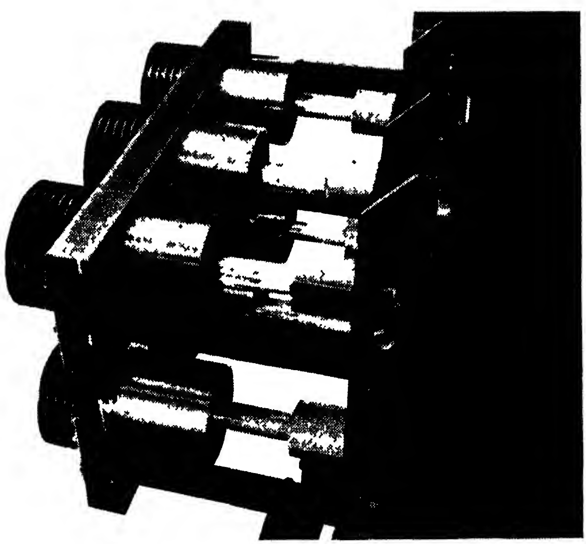


FIG. 10-21.—*Close-up of sliding isolating contacts at rear of circuit-breaker. Both sets in "made" position (The English Electric Co. Ltd.)*

*"English Electric" patent.

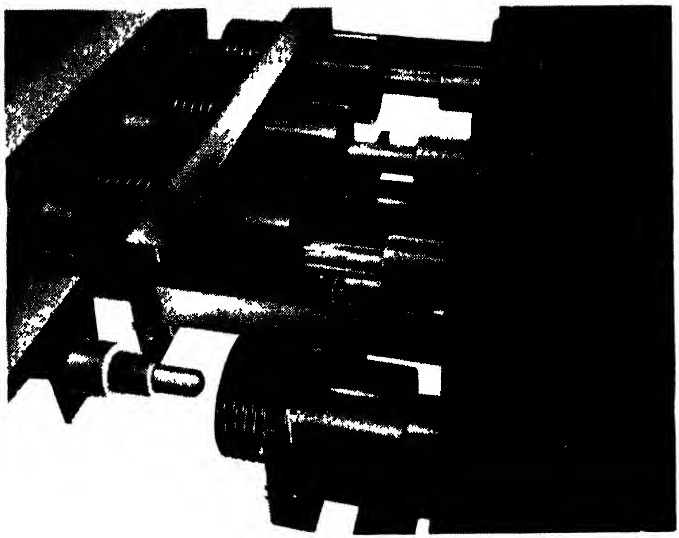


FIG. 10-22.—*Close-up of sliding isolating contacts at rear of circuit-breaker Cable contacts in "made" position and busbar contacts in "isolated" position (The English Electric Co. Ltd.).*

Fig. 10-23 shows a switchboard of 3·3 kV air-break circuit-breaker units as manufactured by A. Reyrolle and Co. Ltd. As in other designs of high-voltage air-break switchgear, integral means are provided for earthing either the cable or the busbars. In those for 3·3 kV and for 250 MVA at 6·6 kV, the isolating contacts on the carriage and fixed housing are linked by hinged blades which can be swung through 90 degrees to take up positions for engagement with additional contacts connected to an earth bar. The principle of this operation is shown in Fig. 10-24 and in Fig. 10-25 is shown the rear view of a circuit-breaker unit on its carriage with the upper set of hinged blades swung down as required for busbar earthing, i.e. as shown at (b) in Fig. 10-24.

The locking-off doors shown in this illustration are earthed metal shutters which automatically cover the busbar and feeder fixed contact orifices when the circuit-breaker is withdrawn and both sets of doors can be padlocked closed. When it is required to earth one side or other of the circuit, the action of changing over the hinged blades to the earthing position automatically immobilises the drive to the associated locking-off doors. The other set can be left padlocked closed. A full set of interlocks ensures that the function of earthing can only be completed in a correct and safe sequence.

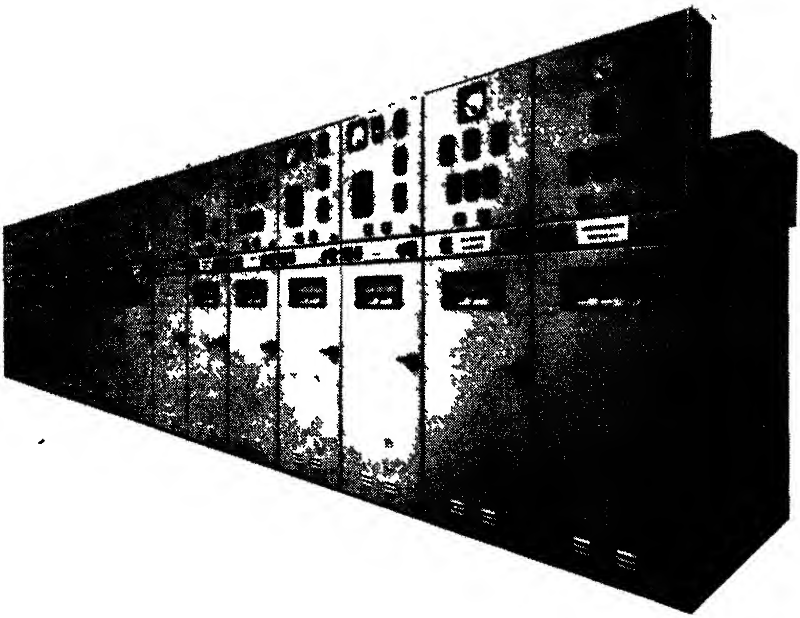


FIG 10-23 *Power station switchboard of 3 3 kV air break circuit breaker units (A Reyrolle & Co Ltd)*

In designs for 11 kV and for 500 MVA at 6 6 kV, earthing is achieved by means of cranked rotatable bushings, the cranked conductors being cast in epoxy resin as shown in Fig 10-26

How this bushing is turned through 180° to make contact with separate earthing contacts is shown in Chapter IX from a study of Fig 9-18, this latter illustration showing a complete cross-section of a 500 MVA unit It shows, incidentally, the considerable use of cast epoxy resin in this unit, including not only all those parts which are cross-hatched but also the voltage-transformer orifice connector, the voltage-transformer windings, the cable-box bushing and the busbar orifice connector This design has been considered in some detail in the I E E paper No 2835 S referred to in the bibliography

(c) COMPOUND-FILLED TYPE

No design of switchgear is more essentially British in conception and design than the type known as "compound-filled" It was in the year 1906 that it was first introduced by Messrs A Reyrolle & Co Ltd , and it is interesting to note that, while many improvements in detail have been made, the essentials of the earliest designs are still to be noted Today nearly all British switchgear makers produce gear of this type in one form or

another, the range extending to higher voltages than the air-insulated types.

In contrast, Continental practice is along the line of open type gear arranged on two, three or even four floors. This may be due to the fact that the greater use of the indoor air-blast and expansion types of circuit-breaker on the Continent does not lend itself readily to metalclad designs. In America, there are designs which approximate very closely to British designs, but, in general, the use of compound-filled gear is by no means as extensive.

There are a number of reasons why this type appeals to British and Commonwealth users. Some of these apply equally to the air-insulated types described in the preceding section, e.g., the readiness with which safeguarding interlocks may be applied leading to greater safety. Others are peculiar to the compound-filled types, as for example, saving in space. This naturally varies with the rating of the equipment, and as the voltage and breaking capacity increase so is the saving in space greater.

At 33 kV, the usual upper limit for indoor gear, the height of a stone cell may be twice that of filled gear, and take up to four times the cubic space. This is in a large degree due to the difference in clearances necessary at 33 kV in air and in compound, the figures being:—

	In air	*In compound*
To earth	8·75 in.	2·5 in.
Between phases	14·0 in.	3·5 in.

Busbar faults in compound-filled gear are less likely, firstly because the filling acts as an additional support to the busbars, and secondly because it excludes the possibility of contamination by dust or pollution and the intrusion of vermin.

As with other things, the type has some disadvantages, first of which is that access to some component items is not always easy in case of trouble, e.g., if the current transformers are in a compound-filled chamber. Secondly, there is a thermal problem with heavy current busbars when compound-filled, and thirdly, the cost is usually greater than that of other types.

Compound-filled switchgear comprises a fixed portion and a moving carriage, generally as described for other types; but, whereas in other types there is considerable similarity as between one make and another, there are variations in the compound-filled design.

As typical of a major variation, Figs. 10-27 and 10-28 may be noted. The former is an example of a type employing vertical isolation, while the latter is an example of a horizontal draw-out type.

It will be of interest to consider various design aspects under the following sub-headings:

(1) Horizontal or vertical isolation

(2) Methods of busbar selection in duplicate busbar designs

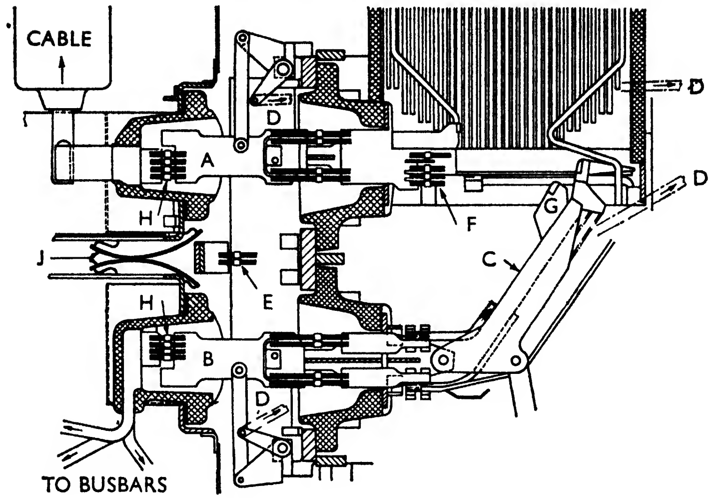
(3) Busbars

(4) Interlocking safeguards

(5) Current transformer enclosures

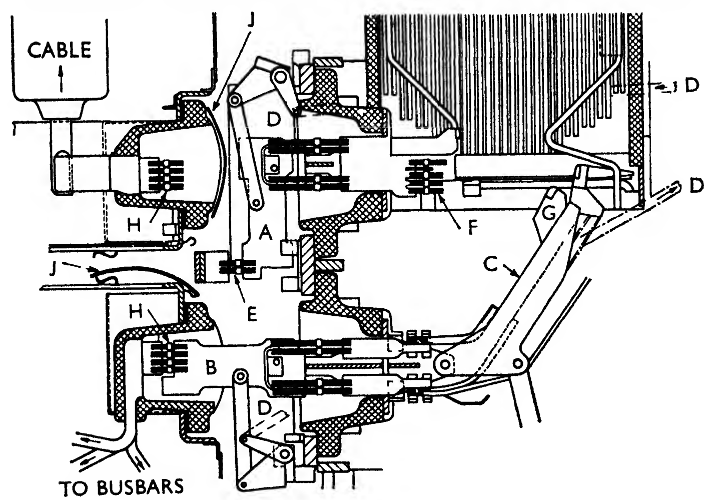
(6) Voltage transformer problems

(7) Miscellaneous.



(a)

SHOWING HINGED BLADE CONTACTS IN SERVICE POSITIONS



(b)

SHOWING HINGED BLADE CONTACTS IN POSITION FOR BUSBAR EARTHING. CABLE ISOLATING ORIFICE CLOSED BY LOCKING-OFF DOOR

NOTE. TO EARTH THE CIRCUIT CABLE, HINGED BLADE B WILL BE *RAISED* THROUGH 90° TO VERTICAL POSITION AND HINGED BLADE A WILL REVERT TO ITS SERVICE POSITION. FOR THIS OPERATION, THE BUSBAR ISOLATING ORIFICE WILL BE CLOSED BY ITS LOCKING-OFF DOOR

FIG. 10-24.—*Schematic diagram showing a part section of an air-breaker circuit-breaker unit with hinged blades for busbar or cable earthing (A. Reyrolle & Co. Ltd.).*

LEGEND. Fig. 10-24.

A HINGED BLADE CONTACT FOR BUSBAR EARTHING
B HINGED BLADE CONTACT FOR CIRCUIT EARTHING
C CIRCUIT-BREAKER (IN OPEN POSITION BUT PLUGGED-IN)
D OPERATING RODS FOR A AND B
E EARTH CONTACTS AND BAR
G MOVING MAIN AND ARCING CONTACTS
F FIXED MAIN AND ARCING CONTACTS
H ISOLATING CONTACTS
J LOCKING-OFF DOORS

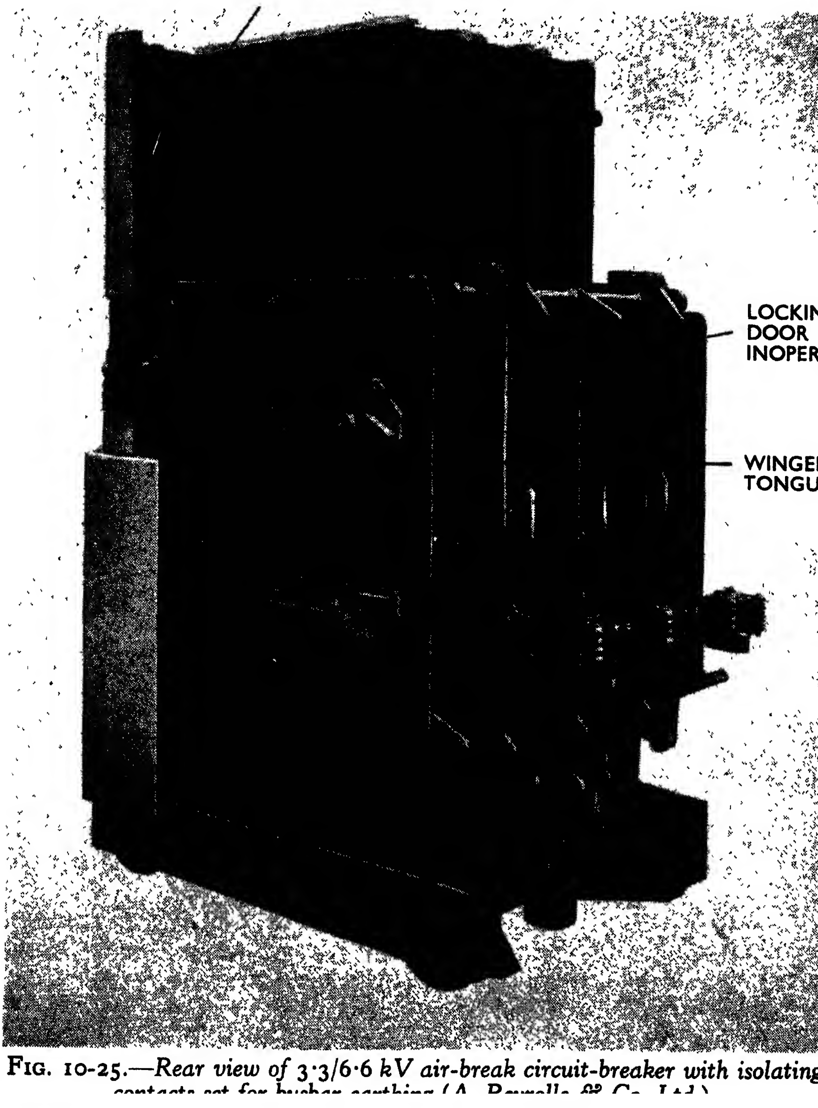


FIG. 10-25.—*Rear view of 3·3/6·6 kV air-break circuit-breaker with isolating contacts set for busbar earthing (A. Reyrolle & Co. Ltd.)*

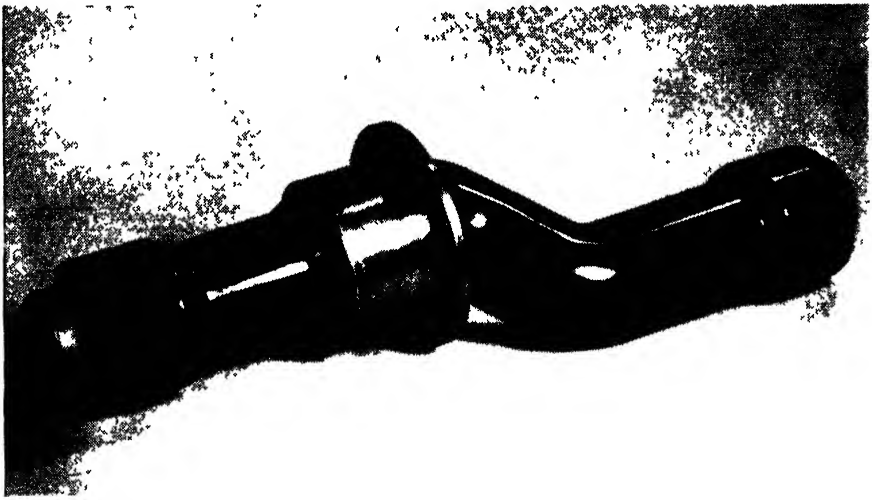


FIG. 10-26.—*Cranked circuit-breaker bushing in epoxy resin (A. Reyrolle & Co. Ltd.).*

(1) *Horizontal or vertical isolation*

From time to time many arguments have been advanced favouring one of these forms of isolation against the other. Some of the arguments have had little justification in fact, but on the other hand, advantages do exist with both types. As will be seen from Fig. 10-27, vertical isolation is achieved by winding down the circuit-breaker carriage exactly as described earlier for the equivalent air-insulated type. In the horizontal type, Fig. 10-28, isolation is achieved by racking out the circuit-breaker along the two side frames. On the latter are fixed toothed racks, while on the carriage there are pinions which engage the racks. With the latter type it is claimed that less manual effort is required and that interlocking is simpler. It is perhaps also an advantage that the dead weight of the circuit-breaker is taken by the side frames. Further it may be necessary with large vertical isolation gear (e.g., 33 kV) to provide a motor operated winding gear as the weight becomes too much for hand manipulation, whereas hand racking is still possible on horizontal types. Against this must be set the fact that to remove the tank from the circuit-breaker, or to remove the complete breaker from the side frames, requires the use of some form of transporter, whereas in the vertical arrangement no such ancillary gear is required.

In the horizontal types, the use of compound-filled hoods immediately above the circuit-breaker becomes necessary to enable a right angle connection to be made between the circuit-breaker and the primary isolating devices. These hoods can be seen in Fig. 10-28. In the vertical isolation type, standard terminal arrangements on the circuit-breakers are used, reducing the length of connections and eliminating the possibility of compound leakage into the circuit-breaker. It is also claimed that vertical

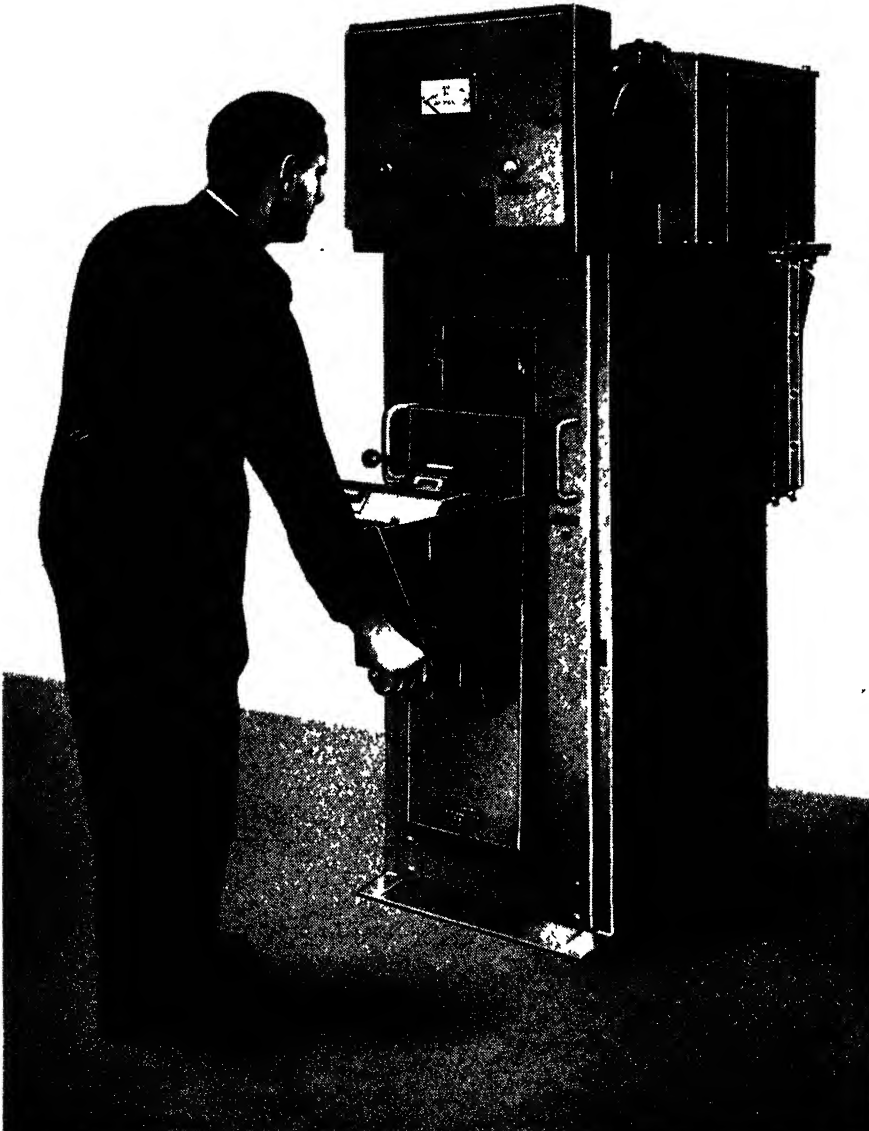


FIG. 10-27.—*Typical compound-filled, vertical isolation unit, 11 kV (Johnson & Phillips Ltd.).*

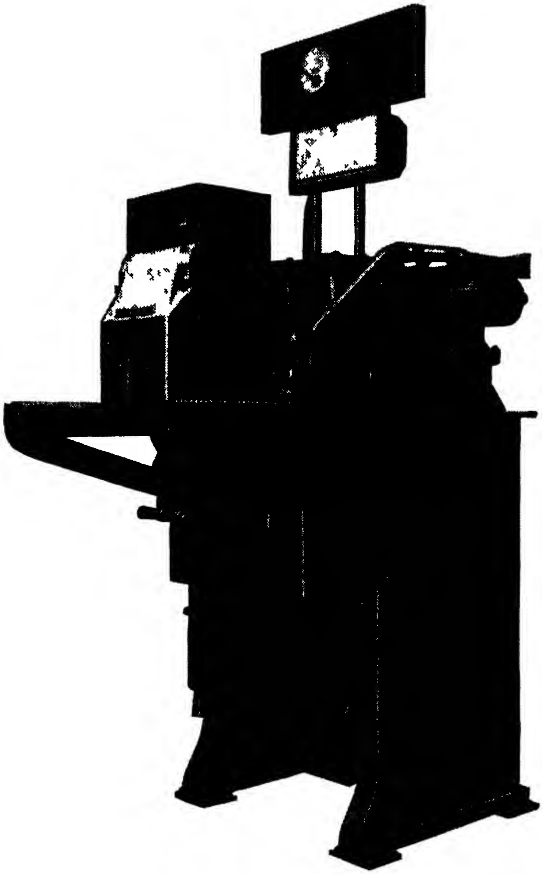


FIG. 10-28.—*Typical compound-filled, horizontal isolation unit, 11 kV (A. Reyrolle & Co. Ltd.).*

isolation with its vertical spout insulators reduces the danger of flash over due to dust, as dust does not tend to collect on vertical surfaces to the extent that it does on horizontal ones.

The location of the busbars in the two types is another variant. In the vertical isolation type, they are carried in separate compound-filled chambers immediately above the circuit-breaker. In the horizontal type, they are placed at the rear of the supporting frames relatively remote from the circuit-breaker. It is sometimes argued that in the vertical isolation arrangement there is danger in that if disaster overtakes the circuit-breaker, it is readily communicated, mechanically, to the busbars, whereas this possibility is not so likely with horizontal isolation. On the other hand, with horizontal isolation, duplicate busbars have to be placed, in their separate chambers, one above the other, so that removal of a section of the lower busbars

1 PLUG-IN TYPE VOLTAGE TRANSFORMER
2 FRONT BUSBARS
3 INSTRUMENT AND RELAY PANEL
4 SECONDARY PLUGS AND SOCKETS
5 D.C. CONTACTOR FOR SOLENOID OPERATED CIRCUIT-BREAKERS ONLY
6 PRIMARY CIRCUIT ISOLATING DEVICES
7 CURRENT TRANSFORMER
8 REAR BUSBARS
9 CABLE BOX
10 OIL CIRCUIT-BREAKER
11 CIRCUIT-BREAKER OPERATING MECHANISM
12 MULTICORE CABLE BOX
13 RAISING AND LOWERING HANDLE
14 CARRIAGE

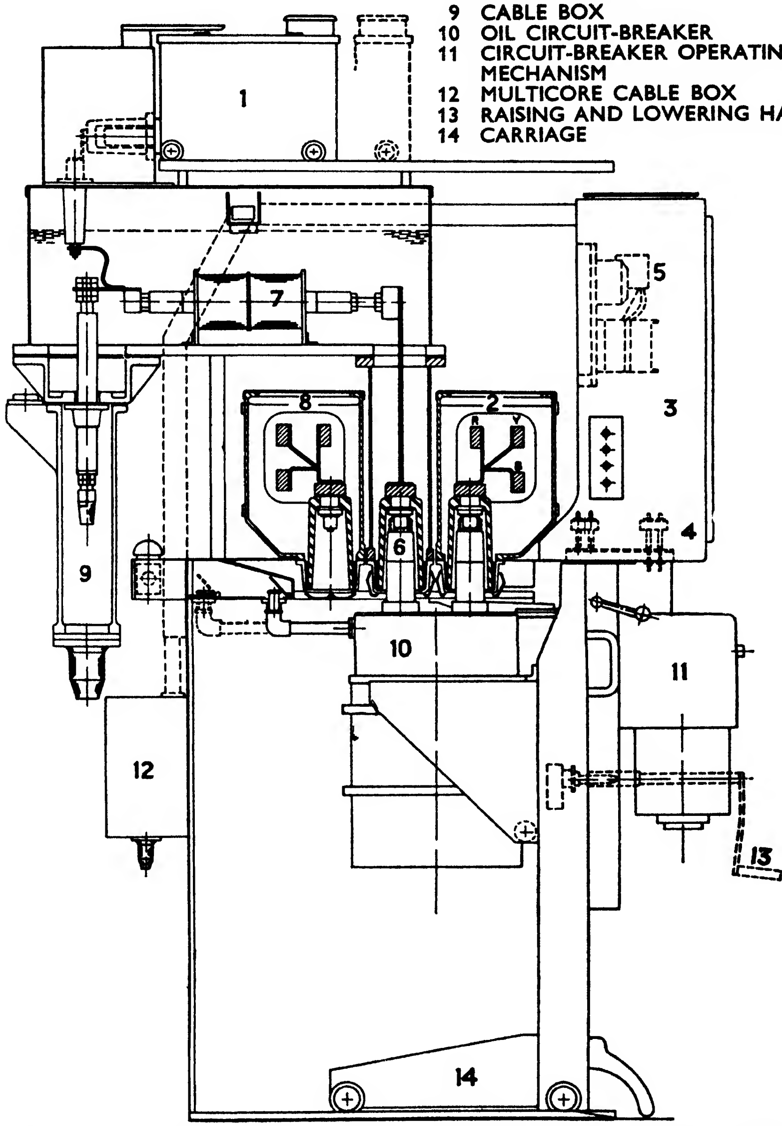


FIG. 10-29.—*Cross-section of typical vertical isolation compound-filled, duplicate busbar switchgear unit (Johnson & Phillips Ltd.).*

involves removal first of an upper section. With vertical isolation this does not arise, as the two sets of busbars can be placed at the same level one beside the other (see Fig. 10-29).

(2) *Methods of busbar selection*

Probably because compound-filled switchgear has been developed for the higher values of voltage and breaking capacity, where system operational conditions more often require the facility of duplicate busbars, many variations of design have been produced whereby selection of the busbar in use can be made.

Most of these will be noted in Chapter XIII but in the vertical isolation type, the most popular form is the transfer breaker scheme where the circuit-breaker is isolated (by lowering) from one set of busbars, moved bodily to another position and then raised to be reconnected to the other sets of busbars. This method has been noted also in the air-insulated types but is seen in more detail in Fig. 10-29. It is of course only suitable for "off-load" selection and other means have to be adopted if "on-load" selection is required. It is a method too which cannot economically be adapted to horizontal isolation types, and in the latter, one or other of the various forms of selection as indicated in Chapter XIII will be employed.

(3) *Busbars*

Careful design and factory assembly is an essential feature when busbars are destined to be solidly encased in compound. It is often necessary to use lower current densities than in air-insulated designs to avoid excessive temperature rises and, unless a user is very sure of his facts, it is unwise of him to specify densities or sections or both, these being left to the designer, the user stating only the current rating he requires.

Current densities will vary with designs but in general figures such as the following represent a fair average:—

Up to 800 amperes	800 amperes per sq. inch
,, ,, 1,200 ,, ...	600 ,, ,, ,, ,,
,, ,, 1,600 ,, ...	450 ,, ,, ,, ,,
,, ,, 2,000 ,, ...	400 ,, ,, ,, ,,

In considering these figures it should be noted that up to 2,000 amperes the busbars usually take the form of solid copper bars narrow in width and increasing in breadth with increase of current. For higher ratings special designs become necessary involving sub-divided busbars or bars forming a hollow square or equal formation. In this connection reference may be made to Fig. 14-2 in Chapter XIV. The use of compound as a filling medium excludes air from the chamber and permits reduced electrical clearances. It gives additional support for busbars against the forces of short-circuit, but unfortunately compound is a thermal insulator. Excessive temperatures must be avoided and careful tests taken to check the design in this respect. As the bars are inaccessible, thermo-couples are used to obtain temperature measurements.

Apart from heating, the designer must bear in mind that placing phase busbars close together increases the losses due to proximity effect but if they are placed well apart a greater volume of compound is needed, thereby reducing thermal capacitance and increasing the ultimate temperature.

Wherever possible the busbars should be placed as close to the surrounding casing as possible as this is the ideal arrangement for heat dissipation, and in some designs chambers are specially shaped to maintain closeness to the busbar formation.

A typical busbar chamber before compounding is shown in Fig. 10-30, while a complete chamber is shown at Fig. 10-31.

The process of filling a busbar chamber is one which demands considerable care and cleanliness. There must be no possibility that extraneous items are concealed within the chamber, as obviously this can lead to disaster later. In filling, the formation of gas bubbles due to over-hot compound must be avoided, air must not be trapped to form pockets, and an expansion space must be left above the compound. The chamber is usually heated prior to filling.

It is an inherent feature in all designs of compound-filled switchgear that joints between unit sections of busbars have to be made on site. This involves the use of joint rings or muffs fitted after the busbar joint plates have been bolted in position. The ring or muff is then filled with compound. In Fig. 10-31 can be seen a rim which takes the muff for the purpose described above.

Copper joint pieces between busbars must be designed to avoid hot-spots and be arranged to allow expansion under load conditions. This is usually taken care of by the use of flexible joints as noted in Chapter XIV.

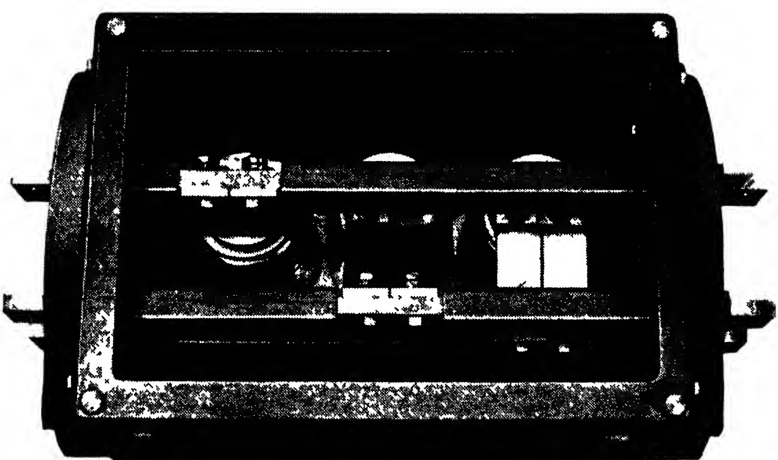


FIG. 10-30.—*Typical busbar chamber before filling with compound. The bars are insulated with synthetic resin bonded paper except at tee-off connections (Johnson & Phillips Ltd.).*

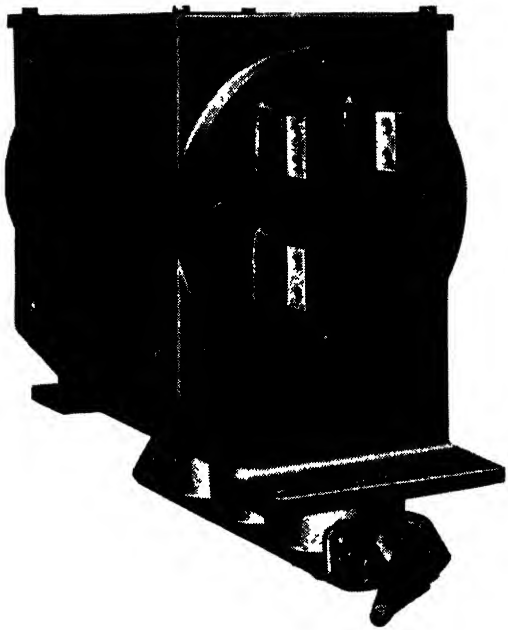


FIG. 10-31.—*Completed compound-filled busbar chamber (Johnson & Phillips Ltd.).*

(4) *Interlocking safeguards*

The range of interlocks required are, in general, the same as those we have discussed earlier for the air-insulated types of gear.

In designs for the higher voltages (22/33 kV) raising and lowering the circuit-breaker by a hand-operated mechanism becomes unwieldy and laborious and in one range (Associated Electrical Industries Ltd.) this function is performed by two lifting rails actuated by four motor-driven lifting screws.

This feature requires that additional interlocks be fitted (a) to switch the motor off automatically at the fully raised or fully lowered positions, (b) to switch off the motor if an attempt is made to raise the breaker with one or both shutters padlocked closed, (c) to prevent the motor being energised when the circuit-breaker is closed and (d) to prevent the motor being energised if the emergency hand raising mechanism is in use.

(5) *Current transformer enclosures*

In early designs the use of solid compound as a filling medium was extended to current transformer enclosures. Later it was realised that this had several disadvantages.

Chief among them was the difficulty which occurred when the need for transformers of a new ratio arose. An increase in circuit capacity can give rise to this condition and while the primary conductors and the circuit-breakers are often of ample capacity to cover the increase, the current transformers must be changed. It is a tedious and difficult operation to remove them if they are embedded in compound and present-day practice provides for oil-filled current transformer chambers.

Owing to the space saving features of compound-filled type switchgear, accommodation for a large number of current transformers is not always possible, particularly on smaller units. Where possible, ring (bar primary) transformers are used and two or even three of these may be mounted on a common primary bar within a small space. A typical arrangement of this is illustrated in Fig. 10-32.

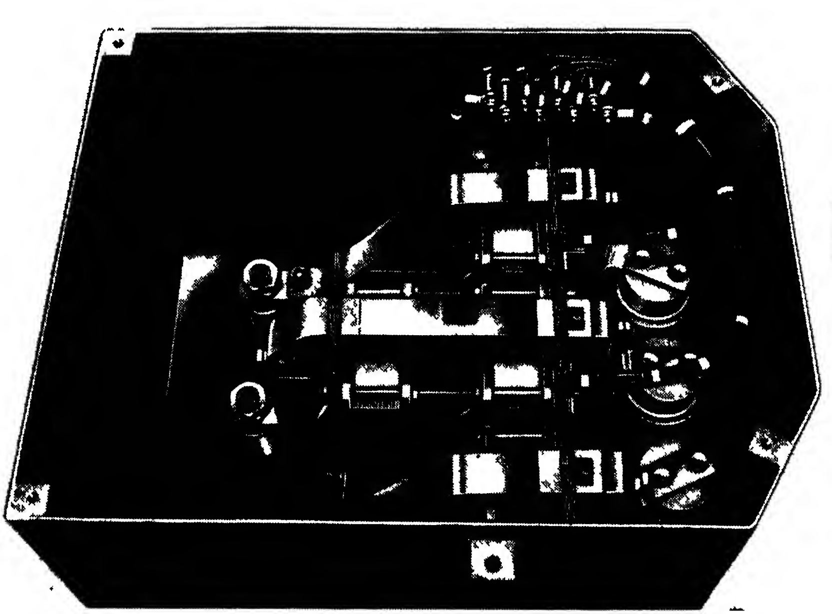


FIG. 10-32 —*Unfilled current transformer chamber for compound-filled switchgear unit (Johnson & Phillips Ltd.).*

(6) *Voltage transformer problems*

Perhaps the most awkward item to accommodate in any type of switchgear is a voltage transformer. This is particularly so where busbar transformers are required, and even more so in the case of duplicate busbar systems.

In the vertical isolation type of gear busbar voltage transformers can be accommodated on the top of the unit but this requires a set of spout orifices and sockets on the busbar chamber. A typical example of this is shown in Fig. 10-33.

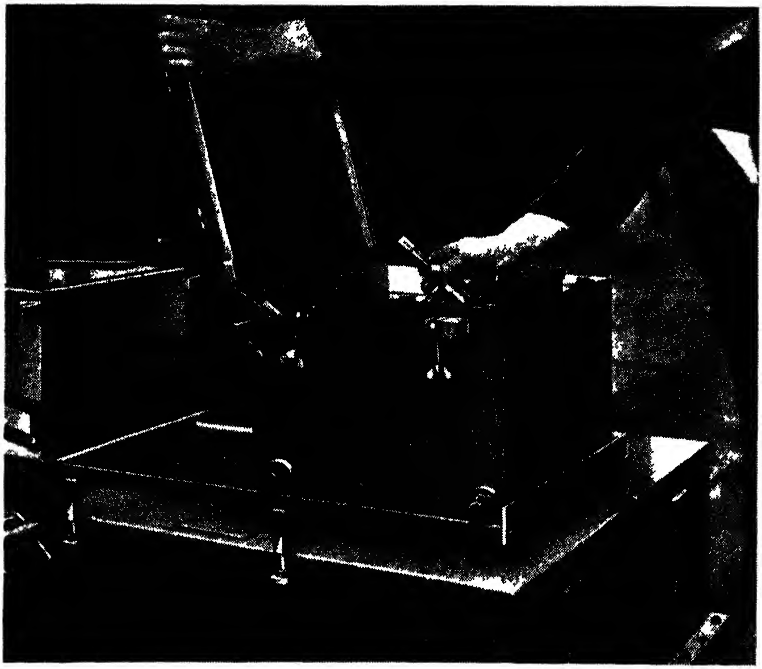


FIG. 10-33.—*Showing busbar voltage transformer mounted on top of compound-filled unit—transformer withdrawn for fuse renewal (Johnson & Phillips Ltd.).*

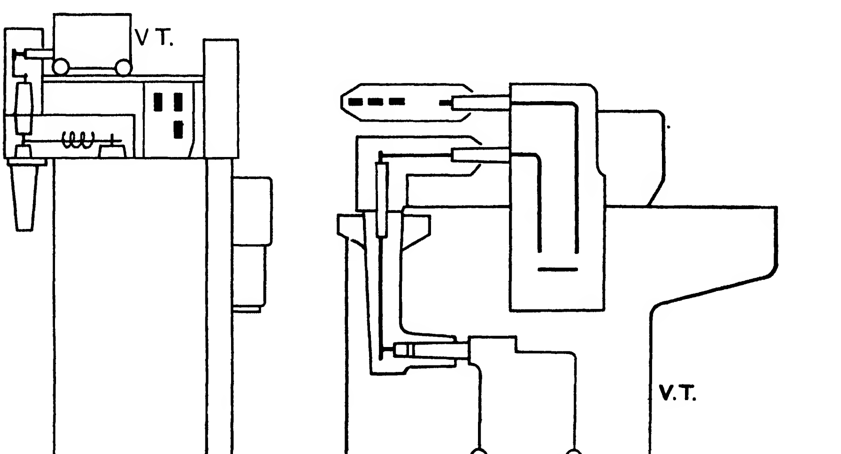


FIG. 10-34.—*Showing voltage transformer arrangements on the cable side of vertical isolation gear and of horizontal isolation gear.*

In the horizontal type of gear, however, voltage transformers for connection to the busbars usually have to be carried on a separate set of side frames which serve no other purpose than to carry the transformer and to provide means for it being plugged-in to the busbars. With duplicate busbars this may mean two separate sets of side frames and two voltage transformers, one arranged to plug-in to one set of bars and the other to the other set of bars.

On the other hand voltage transformers which have to be connected to the feeder or cable side of the circuit do not present the same difficulties and in both types of gear they are usually arranged as shown in Fig. 10-34.

In one design (General Electric Co. Ltd.) for voltages up to 33 kV, not only is vertical isolation used for the circuit-breaker but it is also applied to the voltage transformer which, situated behind the circuit-breaker, is raised and lowered by means of a hand-operated screw hoist built into the side frames. The interior of a unit employing this method is shown in Fig. 10-35.

(7) *Miscellaneous*

In the design of metalclad compound-filled switchgear there are a number of miscellaneous items similar to those we have noted in the air-insulated design.

For example, secondary plug contacts are necessary to which are connected the secondary connections of all current and voltage transformers and other auxiliary circuits. In many designs these circuits are automatically disconnected at secondary plug contacts and Figs. 10-8 and 10-9 show one such design for a vertical isolation unit using circular plugs and sockets of the self-aligning type.

Where such plugs and sockets are used, good contact and alignment is a first requirement, bearing in mind that a single poor contact can be the cause of valuable protective gear failing to function when most needed.

In other designs arrangements are made to maintain the secondary circuits even though the primary circuit is isolated. This involves the use of some form of trailing leads to take up the movement of the circuit-breaker when moved from the fully home to the fully isolated position. When this procedure is adopted, arrangements are made for the leads to be disconnected at a common plug should disconnection be necessary. The argument for fixed secondary circuits is that they are not disturbed every time the primary circuit is isolated and there is therefore greater assurance that good contact has been maintained at these vital points.

Another miscellaneous item of interest is that where secondary connections are isolated as described above, it is necessary to provide some form of jumper box to enable the secondary connections to be re-connected while the primary circuit is disconnected. This is useful for testing protective circuits, interlocks and other secondary circuits.

As in the air-insulated type, busbar, cable, and voltage transformer isolating spouts must have automatic independently operated shutters to cover the fixed live connections in these spouts and Fig. 10-7 is typical. In one design (English Electric) each shutter is fitted with a separate hand-operated mechanism, as shown in Fig. 10-36, which has three positions—open, auto, and close. When the handle is in the auto position the normal

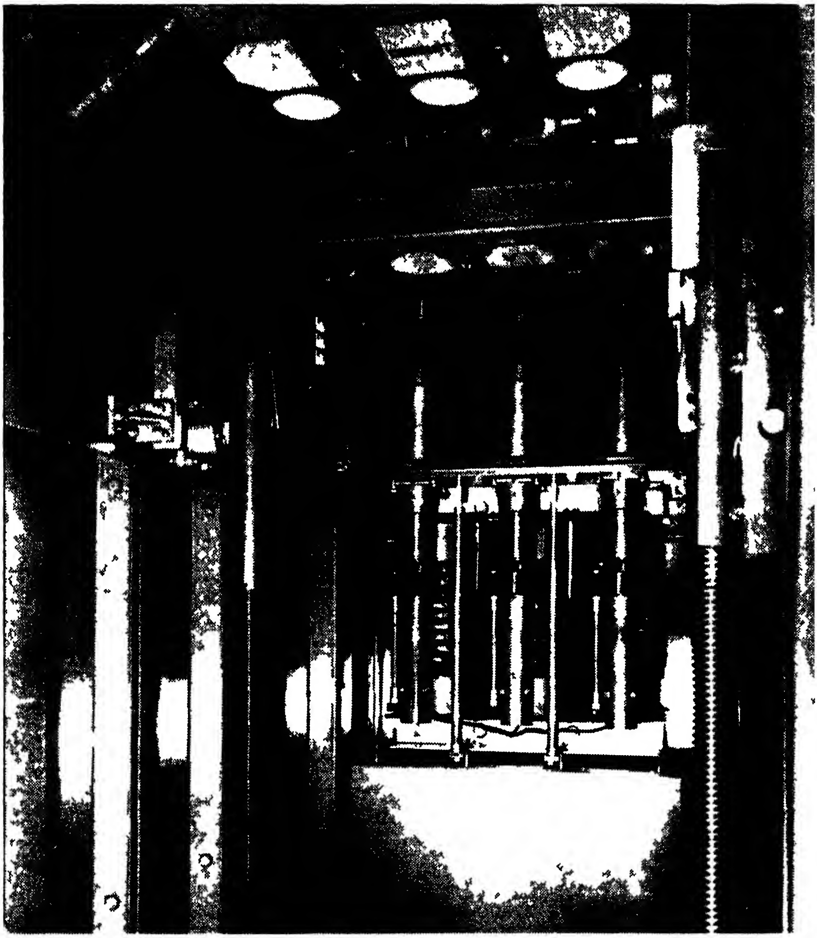


FIG 10-35 —*Interior of vertical isolation unit with breaker removed to show vertical isolation principle applied to voltage transformer The latter is shown isolated and the tank lowered (The General Electric Co Ltd)*

automatic mechanism functions to open or close the shutters In the other two positions operation of the shutters is independent of the automatic mechanism, but the open and close lever positions are overridden by the next racking movement of the circuit-breaker

Some examples of both vertical and horizontal isolation compound-filled switchboards are given in Figs 10-37 to 10-41

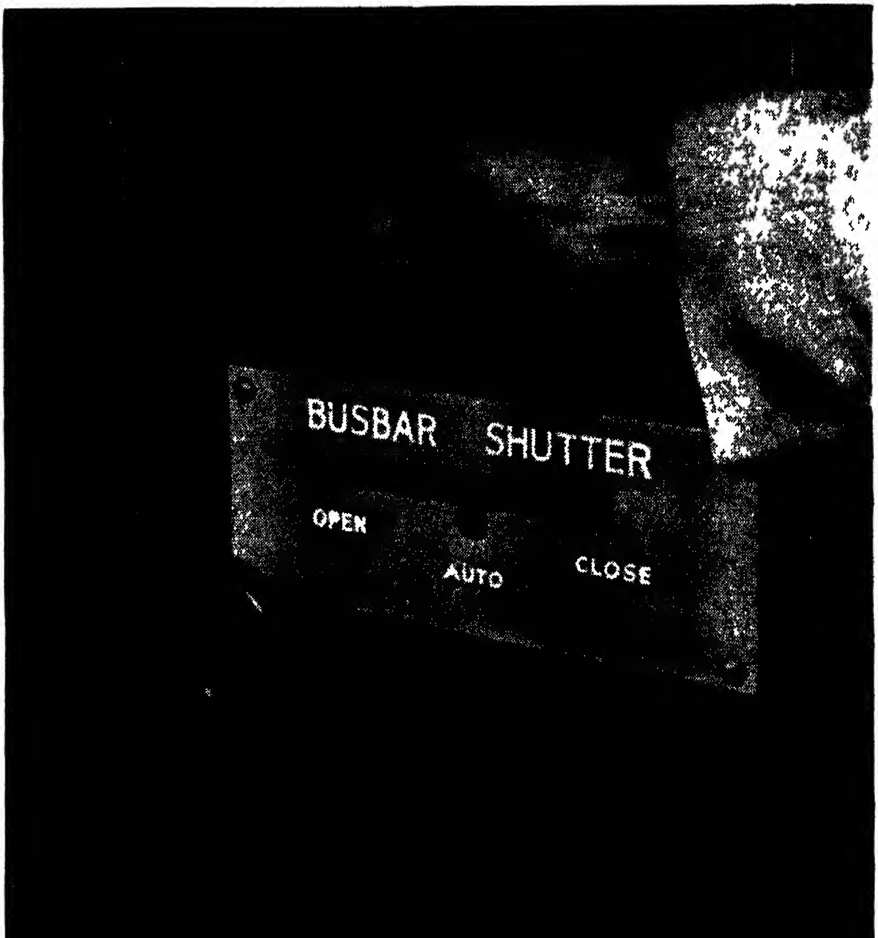


FIG 10-36 —*Busbar orifice shutter setting lever being moved from open to auto position (The English Electric Co Ltd)*

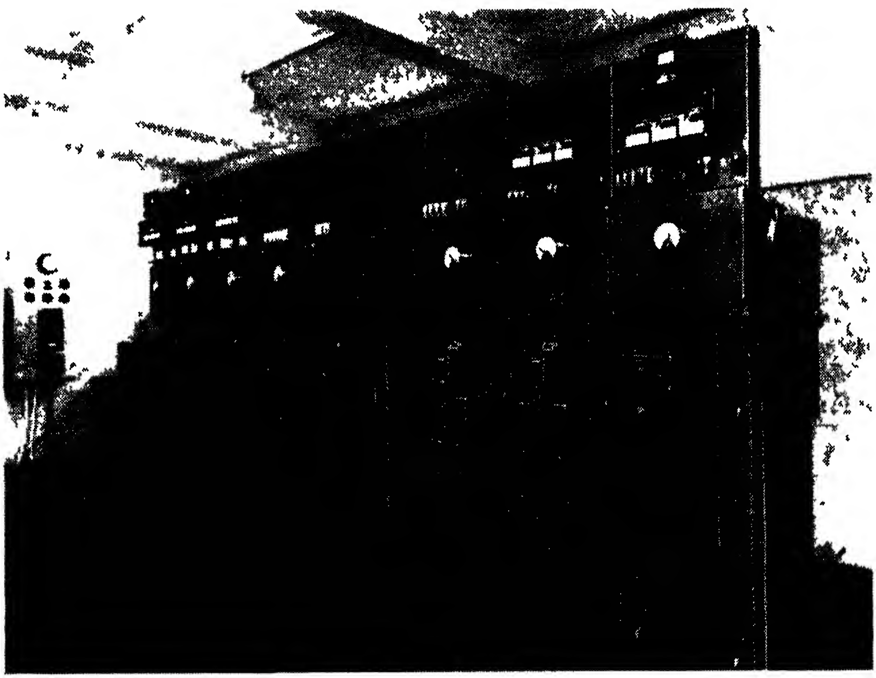


FIG 10-37 —9-panel *compound-filled vertical isolation switchboard single busbar, with hand and spring-operated closing mechanisms. Up to 11/15 kV (Johnson & Phillips Ltd)*

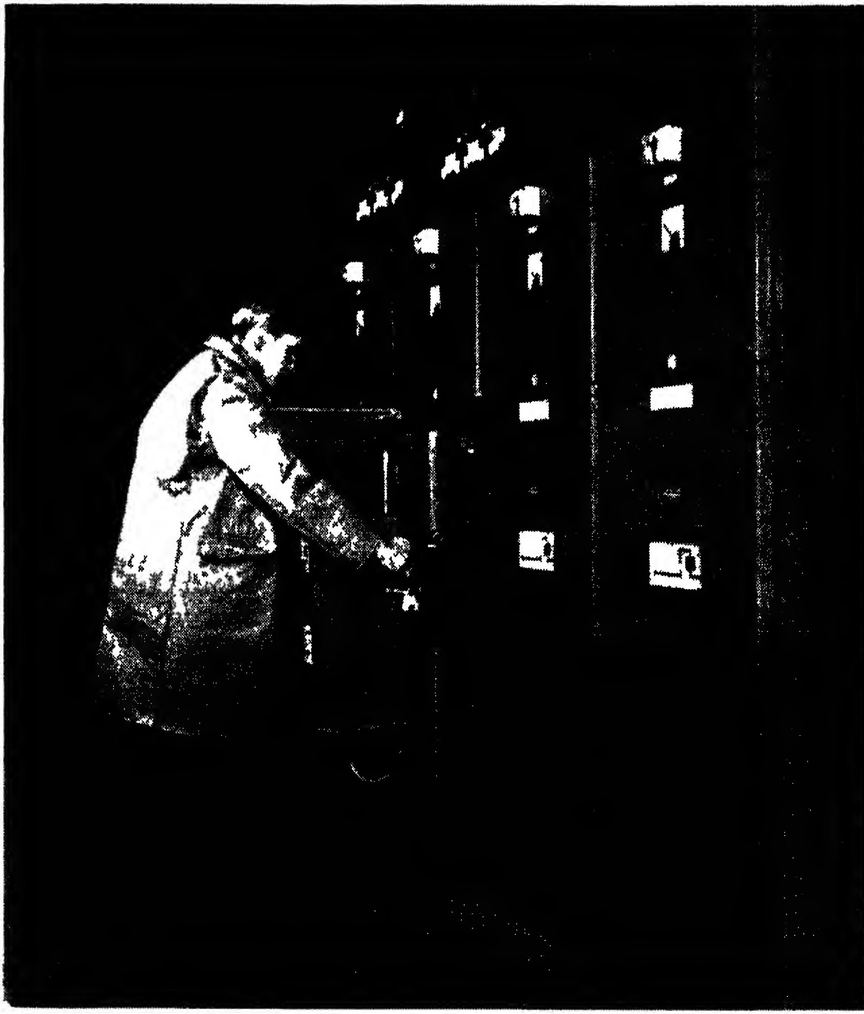


FIG 10-38 —*4-panel compound-filled, vertical isolation switchboard, single busbar with operator closing circuit-breaker by hand Note the mechanical indicator in form of mimic diagram to show the state of the unit Up to* 11/15 *kV* (*The English Electric Co Ltd*)

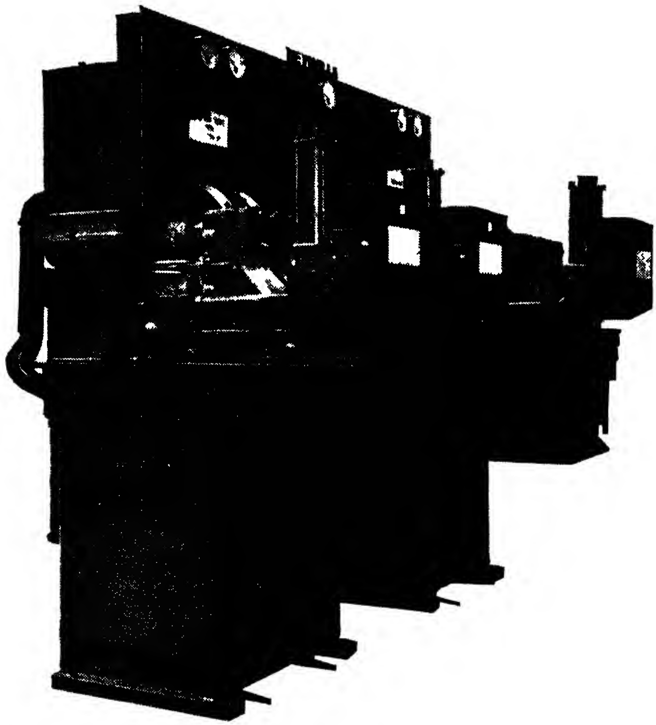


FIG. 10-39.—*3-panel compound-filled horizontal isolation switchboard—11 kV (A. Reyrolle & Co. Ltd.).*

FUSE-SWITCH AND RING MAIN UNITS

For a number of years the fuse-switch (or switch and fuse) has existed in various forms, some with and some without three phase tripping. The use of similar switchgear for the control of certain circuits where the use of an oil circuit-breaker is costly in relation to the importance of the circuit to be controlled is now well-established. Earlier designs were generally of an outdoor type and found greatest application in controlling rural transformers or lines but later developments both in Britain and America have been in the direction of indoor types, and attention was focused on such developments in two I.E.E. papers* in which the greater use of the load-breaking oil switch coupled with h.v. h.r.c. fuses was advocated. The development has been coupled with the use of the now well-known tripping fuse which operates to trip out the load-breaking switch when only one fuse functions.

Although the paper by Wood, as its title implies, deals extensively with low-voltage systems, consideration is also given to the means of protecting and switching h.v. circuits, particularly transformers. The following extract is important in relation to our consideration.

**See Bibliography papers by (1) B. Wood and (2) K. Dannenberg and Professor W. J. John.*

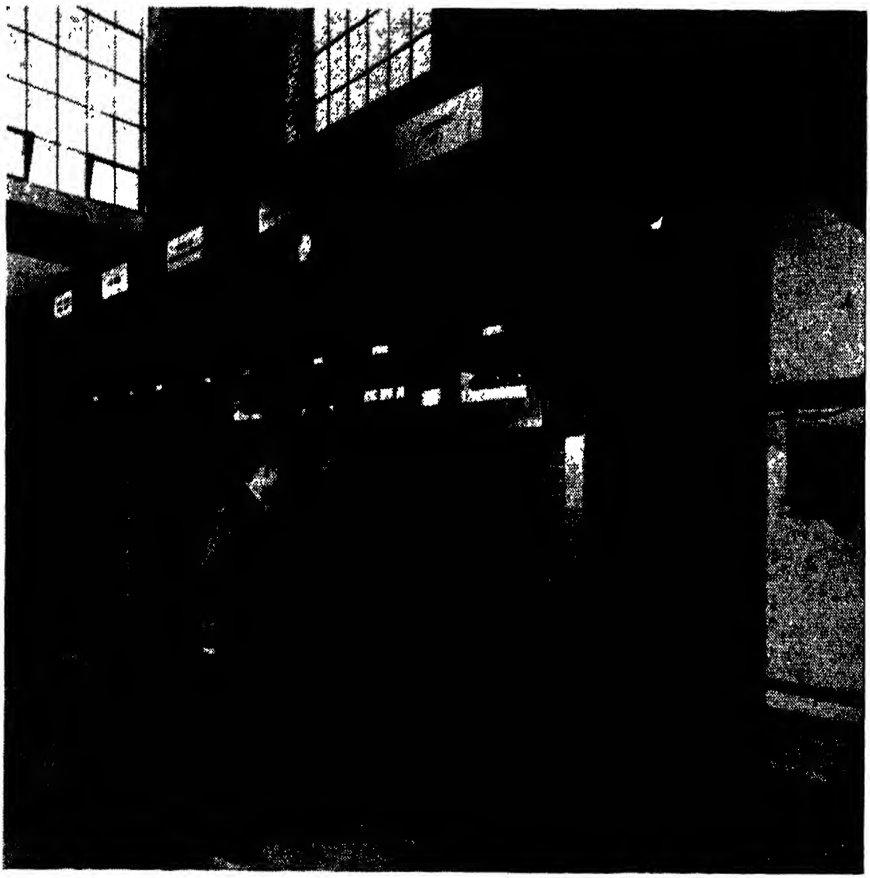


FIG. 10-40.—33 *kV compound-filled, vertical isolation switchboard. Note the roller shutter which masks the circuit-breaker carriage operating mechanism etc. to give clean frontal appearance (The General Electric Co. Ltd.).*

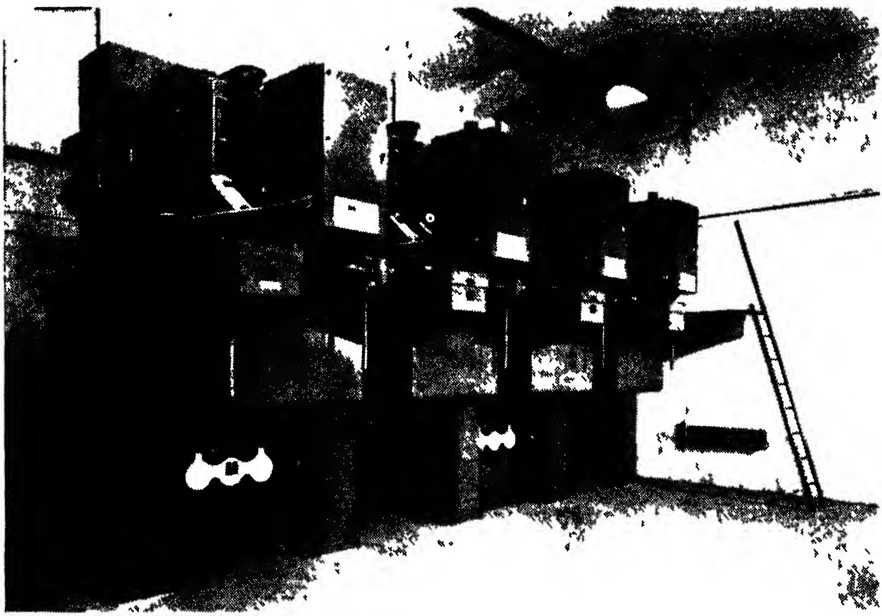


FIG. 10-41.—*4-panel compound-filled horizontal isolation switchboard with duplicate busbars—22 kV (A. Reyrolle & Co. Ltd)*

"The protection of transformers operating in parallel is normally assumed to involve relays. It is considered however that the distribution centre can be adequately protected against faults entirely by fuses, namely a high-voltage fuse and the low-voltage fuses already referred to

"The high-voltage fuse must be chosen to give discrimination over the low-voltage fuses under all circumstances, and must be of adequate rupturing capacity in accordance with the fault duty on the high-voltage system.

"Oil or tetrachloride quenched designs are available but the sand-filled design is preferable.

"A manually operated isolator on the h.v. side capable of breaking magnetising current is also necessary. The fuses can be combined with the h.v. isolator to give automatic three phase isolation on single phase faults and, if desired, the low-voltage isolator could also be intertripped."

The second paper, which deals extensively with the design and performance of h.v. h.r.c. fuses of the tripping type includes the following statement.

"In the load-breaking switch and fuse combination, the switch is simple and inexpensive, being relieved of the duty of rupturing short-circuit currents, a task now undertaken by the fuse. Also the current

through the switch, instead of being the short-circuit current, is now limited by the melting current of the fuse, and this results in a lightening of the current carrying parts.

"This simplification is possible because it is easier to embody provision for dealing with short-circuits and heavy overloads in a fuse rather than in a switch. The switch, dealing only with load switching operations and light overloads, can be made as fully automatic as an ordinary circuit-breaker. The fuses will embody a striker-pin to ensure three phase operation under fault conditions. An application for which this combination will be particularly suitable is that of controlling and protecting small and medium capacity transformers. Up to about 1,000 kVA at 11 kV, the orthodox oil circuit-breaker is more expensive than the transformer which it protects."

The conditions under which the use of h.v. fuse-switches are most favourable may well be reviewed. In the first place, it can be stated that there can be no intention of superseding the circuit-breaker because in many applications the latter is indispensable. Where, however, the system conditions indicate fault values of 250 MVA at 6·6 kV or 11 kV or 150 MVA at 3·3 kV, the cost of a circuit-breaker equipment is expensive for those circuits which control auxiliary plant of secondary importance.

Examples of this are station services, auxiliary transformers, small rectifier circuits, etc. The capacity of such circuits may only be small, e.g. 50 or 100 kVA, and yet, because of the high level of fault at the switchboard, the control apparatus must have a breaking capacity equal to the switchboard short-circuit value. Therefore with this type of circuit it is at the higher values of breaking capacity that the load-breaking switch with fuses is worthwhile and most economical.

The foregoing implies that (a) the requirements shall be for the simplest circuit equipment without expensive relaying or metering, and (b) the design must be such as to line up with the normal form of circuit-breaker equipment to be used.

A design of unit to meet this specification is shown in Fig. 10-42. The busbars in this arrangement may be air-insulated or compound-filled and are located so that the unit can be directly lined up with other types of gear as shown in Fig. 10-43. This switchboard incorporates a metalclad circuit-breaker on the left, a fuse-switch in the centre and a wing-isolator on the right. It can be seen that the dimensions of the fuse-switch unit are such that it can be completely replaced by a circuit-breaker unit if and when this is desired.

Examination of Fig. 10-42 shows that the load-breaking oil-switch is accommodated in a separate enclosure immediately below the busbar chamber, to which access is obtained by removal of a top cover plate D. The three blades are coupled to an operating shaft above oil level as seen in Fig. 10-44 and this, in turn, is linked to a closing mechanism of the free handle type. A shunt trip can be fitted for remote tripping or for intertripping with other apparatus; for example the tripping of the circuit-breaker on the l.v. side of a power transformer can cause opening of the h.v. fuse-switch or, in rectifier circuits, opening of the d.c. breaker can cause opening of the fuse-switch. The oil switch, rated for a normal current of 400 amperes, is capable of breaking this value of current.

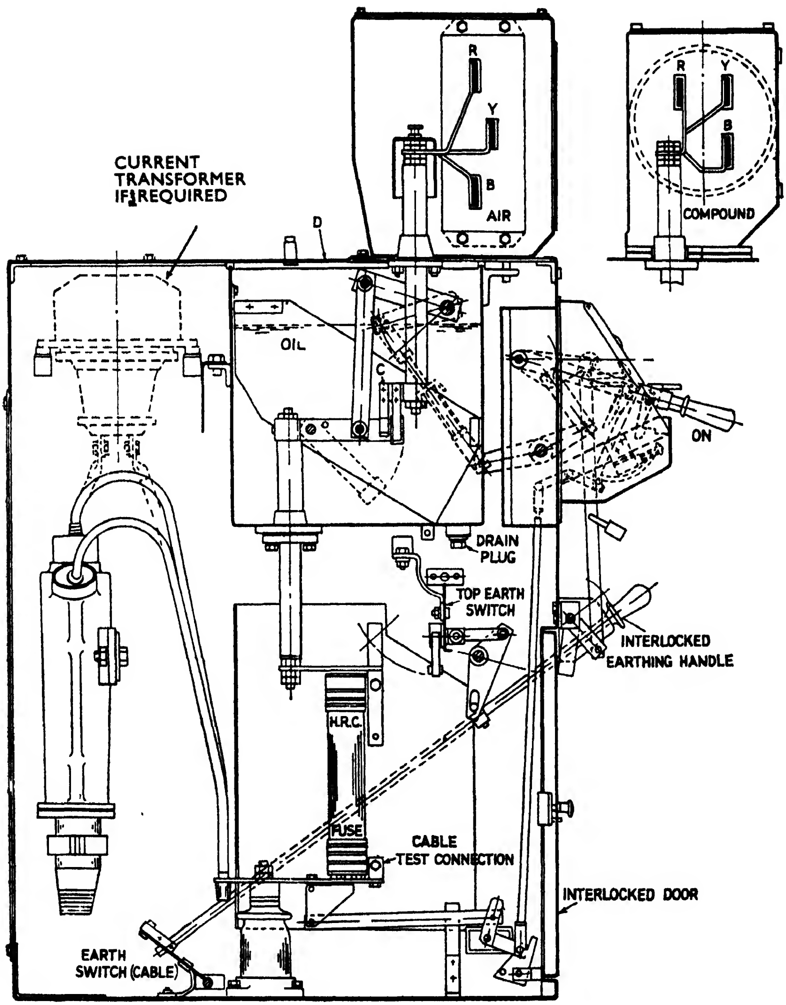


FIG. 10-42.—*Fuse-switch unit showing principal components (Johnson & Phillips Ltd.).*

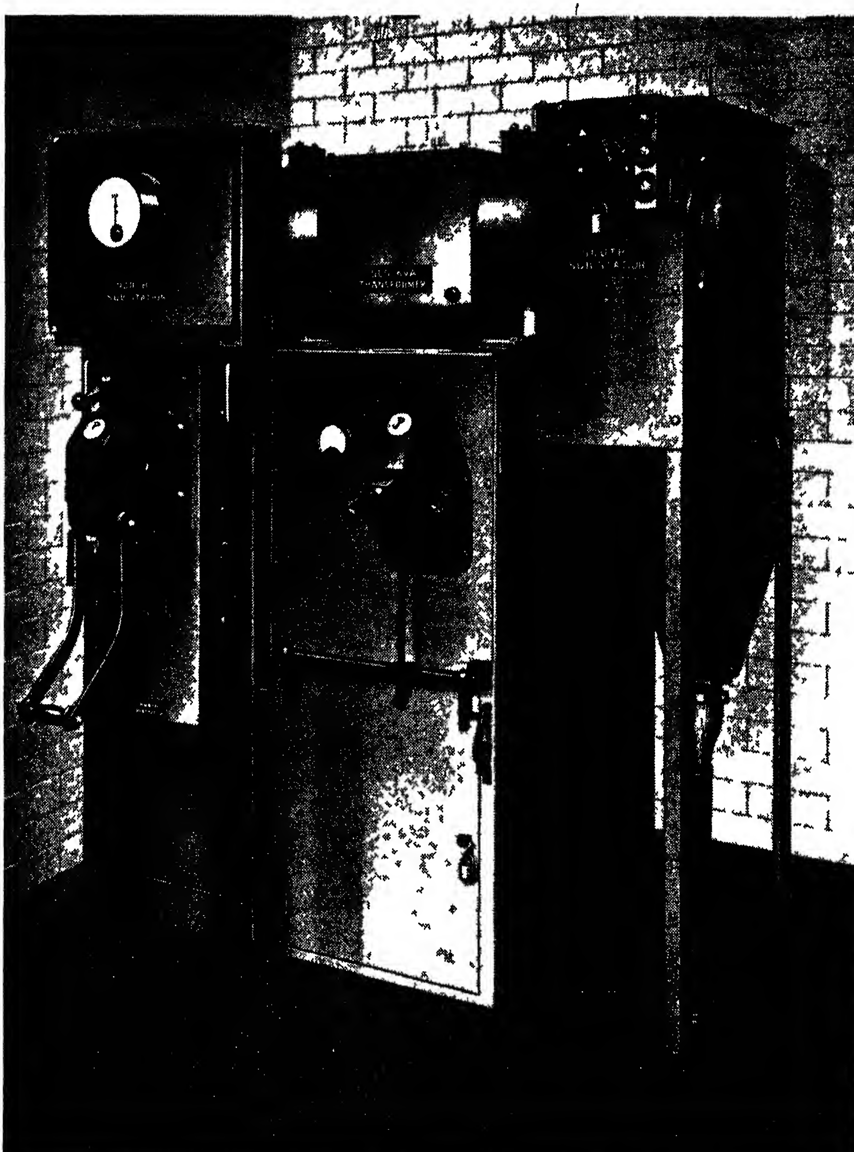


FIG 10-43 —*Switchboard with compound-filled busbars comprising circuit-breaker unit (left) fuse-switch unit (centre) and an incoming wing isolator (right) (Johnson & Phillips Ltd)*

Porcelain clad fuses of the h.r.c. type are used as shown in Fig. 10-45. They incorporate a striker pin to actuate the opening of the oil switch even when only one fuse operates; these fuses lock out on operation to prevent reclosure of the switch until a new fuse has been fitted.

Air insulated fuses are used, the advantages of which are:—

(1) The fuses can be readily inspected without disconnecting them from their normal position.

(2) The problem of oil leaking into the fuse cartridge does not arise and the fuses do not require oil-tight seals.

(3) The fire hazard is almost non-existent.

(4) For a given current size and voltage rating the air insulated fuse is physically larger than a correspondingly rated oil-immersed fuse and therefore has greater internal clearances and a stronger mechanical construction.

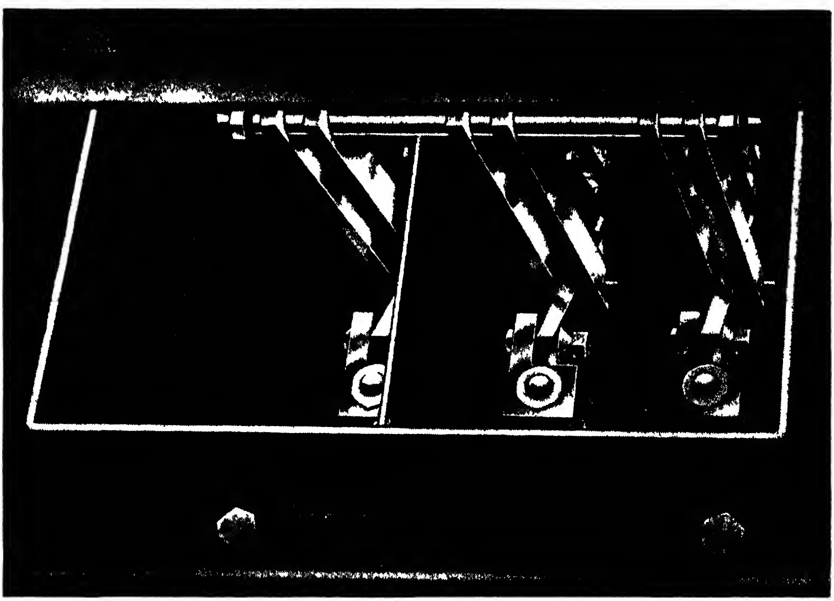


FIG. 10-44.—*Interior of oil-switch showing blades and contacts. One phase barrier removed for clarity (Johnson & Phillips Ltd.).*

A full complement of interlocks makes the unit safe against incorrect operation, and, the interlocking mechanism being external (and therefore visible), an operator can always observe the operating sequence. So that the interlocks cannot be dismantled, and thereby defeated, a welded and

riveted construction is adopted. The interlocks provided make it impossible to:—

(1) Close the switch with the fuse compartment door open.
(2) Open the fuse compartment door with the oil switch closed.
(3) Open the fuse compartment door without first earthing.
(4) Reclose the switch after any fuse has operated.
(5) Earth the circuit with the oil switch closed
(6) Reclose the switch without resetting the time delay device

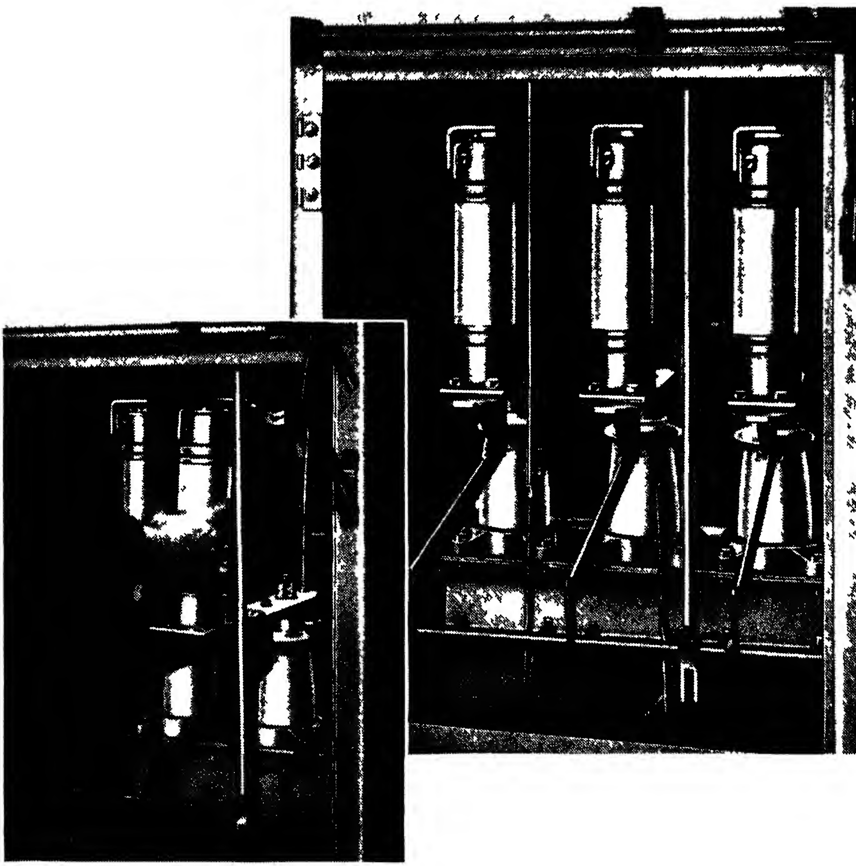


FIG. 10-45 —*Interior of fuse compartment showing the fuses in position. Beneath each fuse can be seen the trip bar which is coupled by means of the vertical rod to the oil switch operating mechanism Inset shows the ease of access to the fuses for replacement and maintenance. (One phase barrier removed for clarity.) (Johnson & Phillips Ltd).*

It will be noted that the earthing switch is arranged to effectively earth all conductors which are accessible when the fuse compartment door is open. It also ensures that the outgoing side of the circuit is dead and earthed before this door can be opened.

The time delay is a mechanical safety device which prevents the switch from opening until a predetermined time—usually 5 seconds—has elapsed after the blowing of a fuse. Thus, when closing on to a fault, the operation of the fuse does not prevent the switch being closed home, and there is no possibility of the switch ever being called upon to carry out or assist in fault clearance.

Facilities are provided for high voltage pressure or current injection tests to be made, the design being such that the circuit to be tested must be earthed prior to testing and then earthed again before disconnecting the test apparatus. Indicating ammeters can be provided, these being operated from wound type current transformers fitted in the rear of the unit.

The satisfactory service given by any type of fuse-switch depends to a large extent on the correct selection of fuse rating for the particular application. Criticism due to unwanted operation can often be traced to haphazard selection, as for example by selecting a fuse rating approximately equal to the full load circuit in the circuit to be protected. Correct selection must be related to the particular application with due regard to any switching-in surges which may occur e.g. on transformer and motor circuits, and to the relation of the fuses with any others, either h.v. or l.v. and to other protective gear.

Typical ratings recommended for transformer and feeder circuits are those given in Table 10 : 1 but noting that these are based on the characteristics of a particular make of fuse (E.M.P. Electric Ltd.) and the suggested ratings may well be modified for other makes.

TABLE 10 : 1

Transformer control							Feeder control	
Rating	11 kV		6·6 kV		3·3 kV		Max. feeder load current	Fuse rating
	Normal current	Fuse rating	Normal current	Fuse rating	Normal current	Fuse rating		
kVA	amps	amps	amps	amps	amps	amps	amps	amps
15	0·79	6	1·31	6	2·62	6	10	15
25	1·31	6	2·18	6	4·36	10	20	25
50	2·6	10	4·4	10	8·7	15	35	40
100	5·3	15	8·7	15	17·5	25	45	50
200	10·5	20	17·5	25	35·0	45	55	60
250	13·1	20	21·8	30	43·7	55	60	65
500	26·3	35	43·7	55	87·4	100	95	100
750	39·3	50	65·6	75	131·2	150	145	150

Note—In the above table on recommended fuse ratings, no account has been taken of possible discrimination requirements between low voltage and high voltage circuits, and only the fuse rating in relation to transformer characteristics has been considered.

In the design of gear described, the following ratings are available.

Voltage kV	Normal current (amps)	Fuse breaking capacity rating (MVA)
3·3	up to 200	150
6·6	„ „ 75	250
11·0	„ „ 65	250

and the time/current characteristics of the fuses are those given in Fig. 10-46.

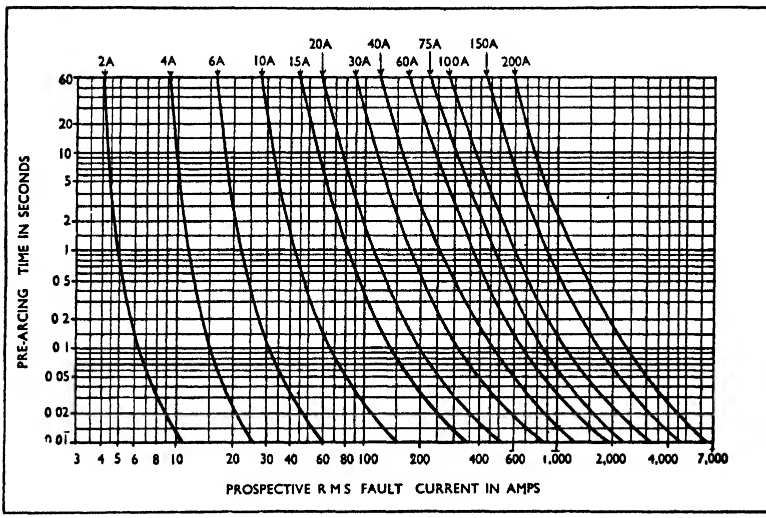
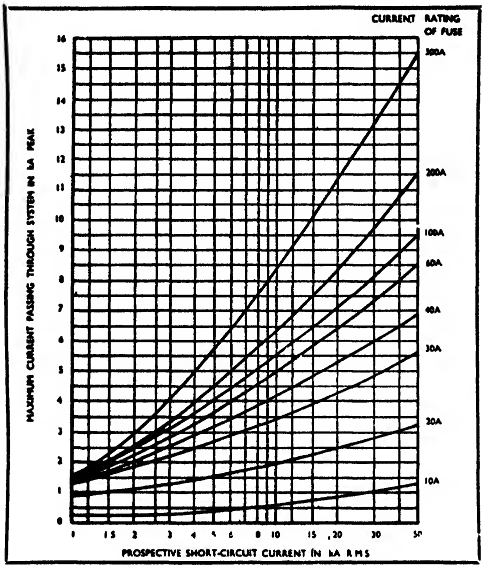


FIG. 10-46.—*Time-current characteristics of high-voltage h.r.c. fuses (E.M.P. Electric Ltd.).*

The importance of cut-off in low voltage h.r.c. fuses is discussed in greater detail in Chapter XII. This is equally important in h.v. fuses of the type illustrated and an indication of its value may be determined by a study of Fig. 10-47. By way of example, let it be assumed that the prospective fault current of a particular network is 30 kA r.m.s. If a fuse-switch of the type described with a fuse rating of, say, 100 amps is installed on that network, then, from Fig. 10-47 it will be seen that the maximum current in the circuit is limited by reason of cut-off to approximately 8·2 kA. This means that all apparatus associated with the circuit in which the fuse appears has to withstand the electro-magnetic forces due to 8·2 kA instead of 30 kA which would be the case if no fuse were present.



Notes—1. The "cut-off" effect at lower fault currents is based on a test circuit in which the maximum short-circuit could amount to 50 kA (r.m s), thereby presupposing a lower rate of rise of fault current at lower fault current values.

2. A tolerance of plus or minus 10 per cent should be allowed when obtaining "cut-off" figures required for deciding operating characteristics of associated switch-gear.

FIG. 10-47. —*"Cut-off" effect of high-voltage h.r.c. fuses (E.M.P. Electric Ltd.).*

As these forces are proportional to the square of the current, the magnitude of the reduction is clearly considerable, as we have shown in Chapter XII. It is this lower value of current to be made by the oil-switch if this should be closed on to a fault.

In some designs of fuse-switch the fuses are under oil and form, in effect, the oil-switch blades, as shown typically in Figs. 10-48 and 10-49.

The fuses may be either non-tripping or tripping types and must be oil-tight. To replace a fuse, a cover immediately above the fuses in the switch "off" position can be opened to permit them to be withdrawn vertically.

In some circumstances the control of a spur feeder or a ring main circuit can be economically controlled by load-breaking fault-making oil-switches instead of the more expensive circuit-breaker or fuse-switch. These oil-switches have already been noted in Chapter VI but it may be repeated here that the design is intended only for breaking load current and not fault

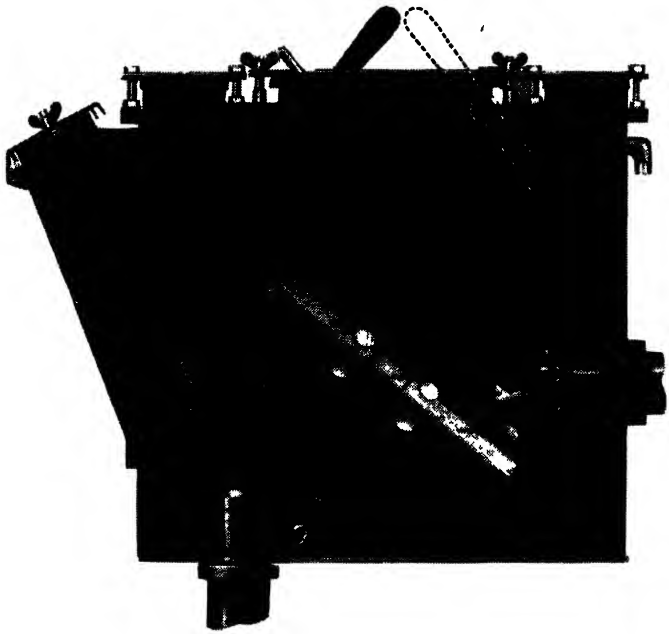


FIG. 10-48.—*Fuse-switch in "on" position (Associated Electrical Industries Ltd.).*

current. The possibility that they may be closed on to a fault however cannot be overlooked and this involves peak values as there is no fuse to limit the value by cut-off. An oil-switch is a non-automatic device, i.e. no protective tripping arrangements are provided and in such circumstances the oil-switch can only be used where the absence of automatic protection is not a disadvantage.

There are many variations of arrangement in this field of high-voltage switchgear, most of them associated with ring main circuits where a tee-off circuit has to be provided. This latter may be controlled either by a fused switch or by a full circuit-breaker equipment and, to cover a wide range of uses, can be arranged in non-extensible or extensible assemblies. Typical of a non-extensible type is that shown in Figs. 10-50 and 10-51.

The circuit arrangements in these units will be more clearly understood from the single line diagrams shown in Figs. 10-52 and 10-53.

Where it may be necessary at some later date to extend a simple ring main equipment or if under original circumstances more than the three-circuit arrangement previously noted is required, gear of the extensible type is essential. In this each unit is individual, each having a set of busbars

which may be air-insulated or compound-filled and so arranged that the busbars can be lined up with those of other types of gear as described in the early sections of this chapter. A typical arrangement is shown in Fig. 10-54 and a single-line diagram in Fig. 10-55.

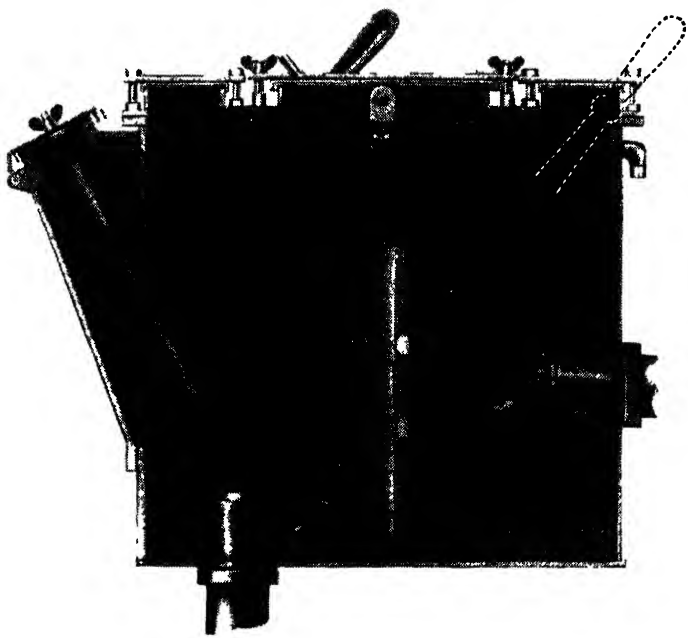


FIG. 10-49.—*Fuse-switch in "off" position (Associated Electrical Industries Ltd.).*

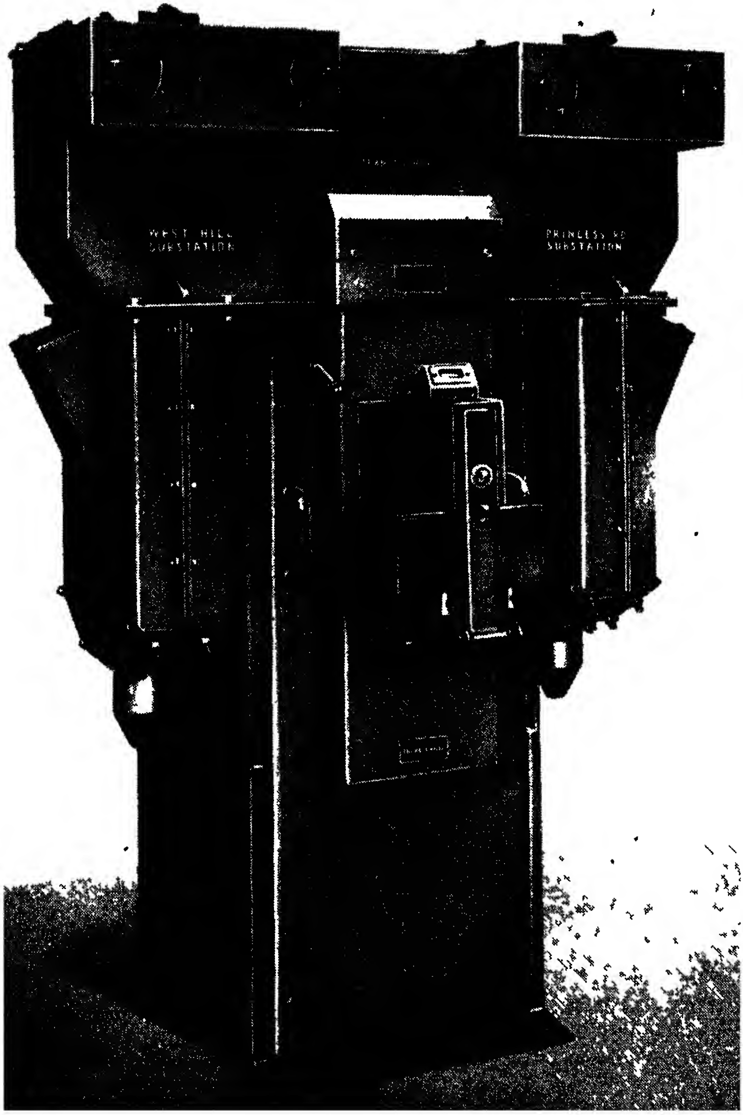


FIG 10-50 —*Ring main unit (non-extensible) comprising two non-automatic ring main oil-switches and one automatic oil-circuit-breaker in the tee-off feed (Johnson & Phillips Ltd).*

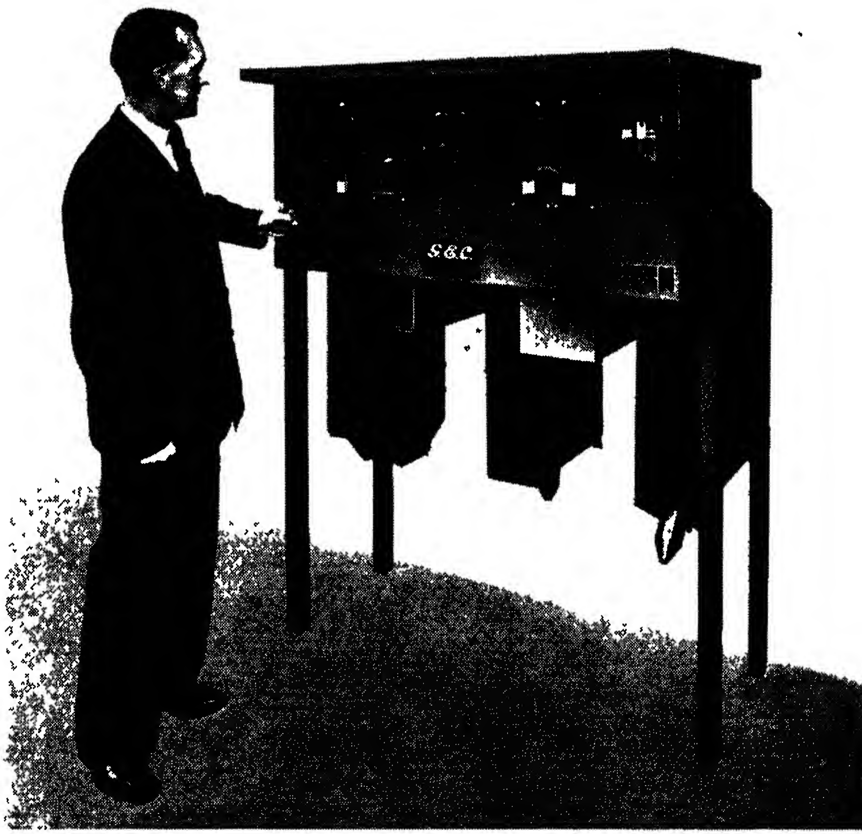


FIG. 10-51.—*Ring main unit (non-extensible) comprising two non-automatic ring main oil-switches and a fused-switch in the tee-off feed (The General Electric Co. Ltd.).*

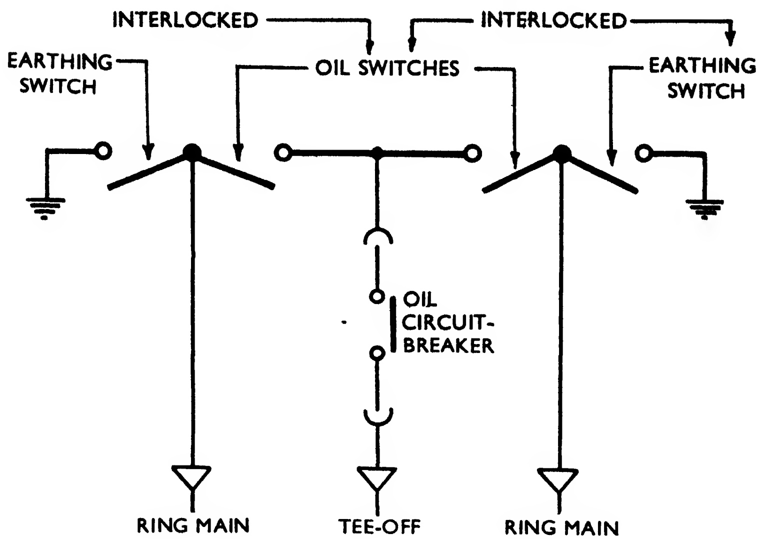


FIG. 10-52.—*Single line diagram for the ring main shown in Fig. 10-50 (Johnson & Phillips Ltd.).*

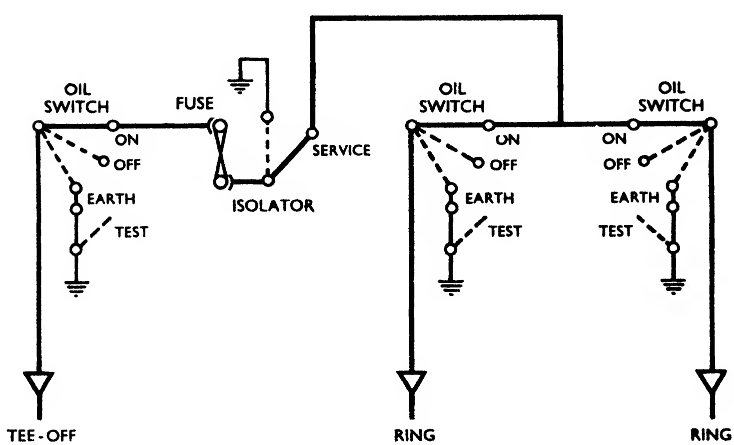


FIG. 10-53.—*Single line diagram for the ring main shown in Fig. 10-51 (The General Electric Co. Ltd.).*

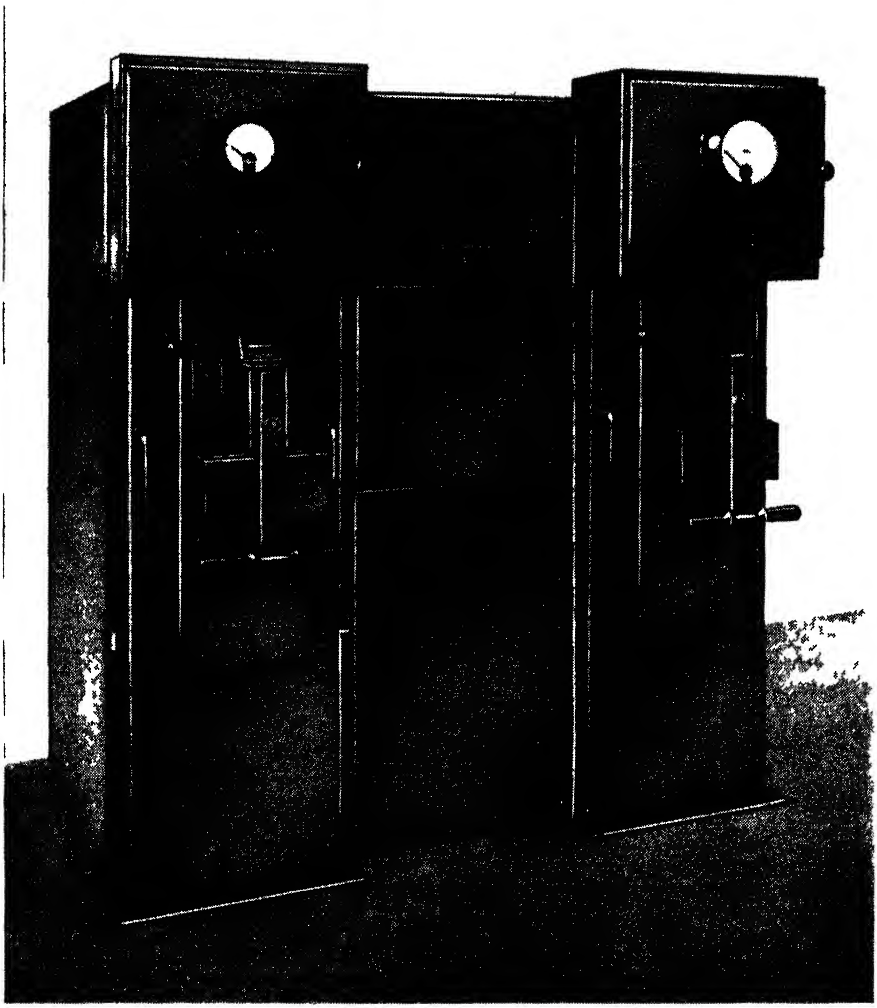


FIG 10-54—*Ring main switchboard of individual units comprising two automatic oil circuit-breakers in ring main and a non-automatic oil-switch in the tee-off feed (Johnson & Phillips Ltd)*

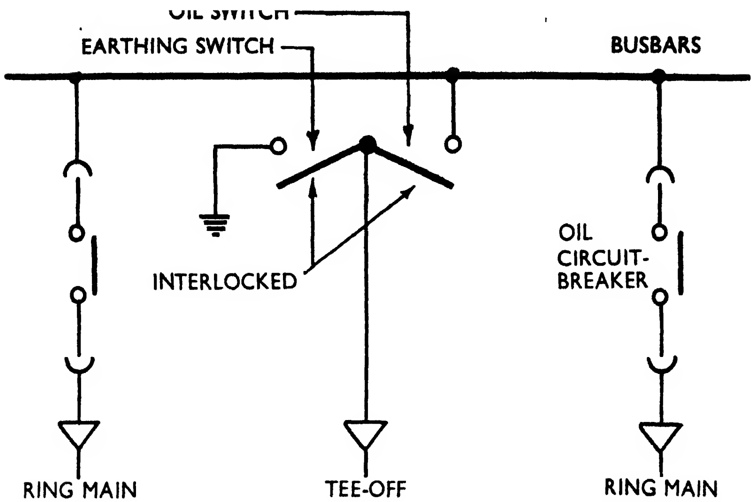


FIG. 10-55.—*Single-line diagram for the ring main switchboard shown in Fig.* 10-54 (*Johnson & Phillips Ltd.*).

All oil-switch units are normally provided with means for cable earthing and testing and because of the onerous duty which closing on to a fault imposes, the mechanism is of the spring-closed manually-operated type. In this, the initial movement of the handle when closing is arranged to store energy in a spring and towards the end of the operation (but before the contacts make) this energy is automatically released to complete the closing operation, rapidly and without hesitation, independently of the operator. Further note of this type of mechanism will be made in Chapter XIX.

BIBLIOGRAPHY

The Calculation and Design of Electrical Apparatus, W. Wilson (Chapman & Hall).

Switchgear Practice, Arthur Arnold (Pitman & Sons).

Switchgear Principles, P. H. G. Crane (Cleaver-Hume Press Ltd.).

"Standardisation of Switchgear," D. E. Lambert, B.Sc. (Eng.) and J. Christie, "Journal I.E.E.," Part I, Vol. 95, No. 91, July 1948.

"Progress in H.V. Metalclad Switchgear," D. R. Davies, "The Metropolitan-Vickers Gazette," April 1941.

"33 kV Metalclad Switchgear for Substations," D. R. Davies, "The Metropolitan-Vickers Gazette," March, 1951.

"Air-Break Switchgear for 11kV 500 MVA," The B.E.A.M.A. Journal, August 1957.

"The Application of Low-Pressure Resins to some High-Voltage Switchgear Designs," T. R. Manley, K. Rothwell and W. Gray. Proceedings I.E.E., Paper No. 2835 S.

"City Distribution in Low-Voltage Networks," B. Wood, "Journal I.E.E.," Part II, Vol. 89, p. 400, 1942.

"A High-Voltage High-Rupturing Capacity Fuse and its Effect on Protection Technique," K. Dannenberg and Professor W. J. John, "Journal I.E.E.," Part II, Vol. 89, p. 565, 1942.

CHAPTER XI

MEDIUM-VOLTAGE A.C. SWITCHGEAR (UP TO 660 VOLTS)

CHAPTER XI

MEDIUM-VOLTAGE A.C. SWITCHGEAR (UP TO 660 VOLTS)

IN this chapter we shall note only those types of medium-voltage switchgear which incorporate oil or air-break circuit-breakers leaving the many forms comprising switches and fuses or fuse-switches to be included in Chapter XII.

For the majority of industrial applications the withdrawal type of oil-break switchgear similar to that shown in Fig. 11-1 is most suitable, being robust, but of simple design with easy and foolproof means of isolation.

This type has an upper limit of current rating of 2 000 amperes and at the higher current ratings will incorporate circuit-breakers having breaking capacities in the range of 15 to 31 MVA. In some ratings, the circuit-breaker is sufficiently small to allow it to be withdrawn along the slide rails

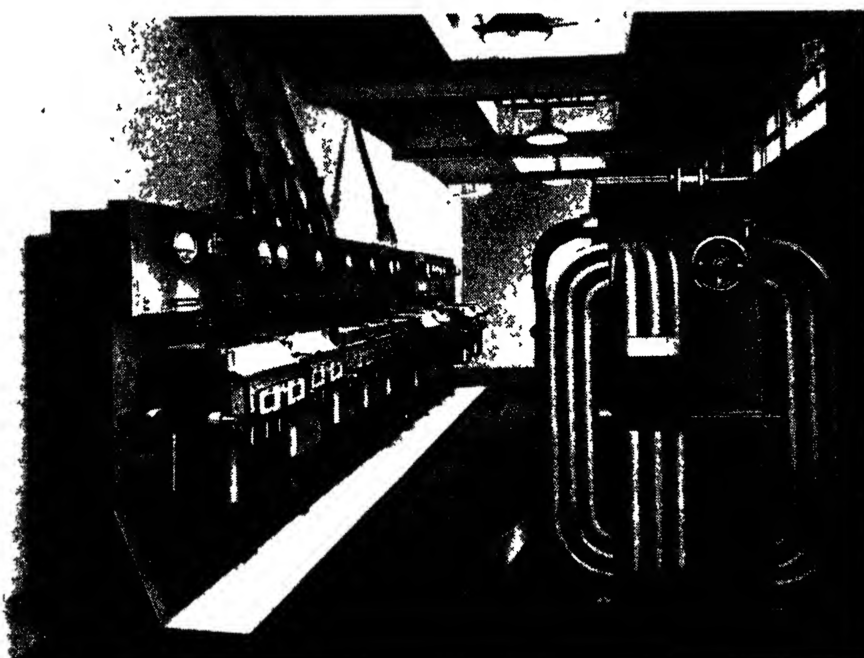


FIG. 11-1.—*Industrial oil-break switchgear, horizontal isolation (Johnson & Phillips Ltd., and by courtesy of the B.S.A. Co. Ltd.).*

by hand, but in larger ratings lever handles are used to assist movement and overcome the normal friction of the isolating contacts. This form of isolation is clear from Fig. 11-2, the withdrawal handle being seen hanging immediately in front of the upright supporting the slide rails.

In this class of gear, the overload trip coils are very often of the series type, but current transformer operated coils may be necessary in a number of circumstances and one way in which three ring type current transformers are accommodated under the top hood above the circuit-breaker is shown in Fig. 11-3. Current transformers will also be required where metering or relay forms of protection are used.

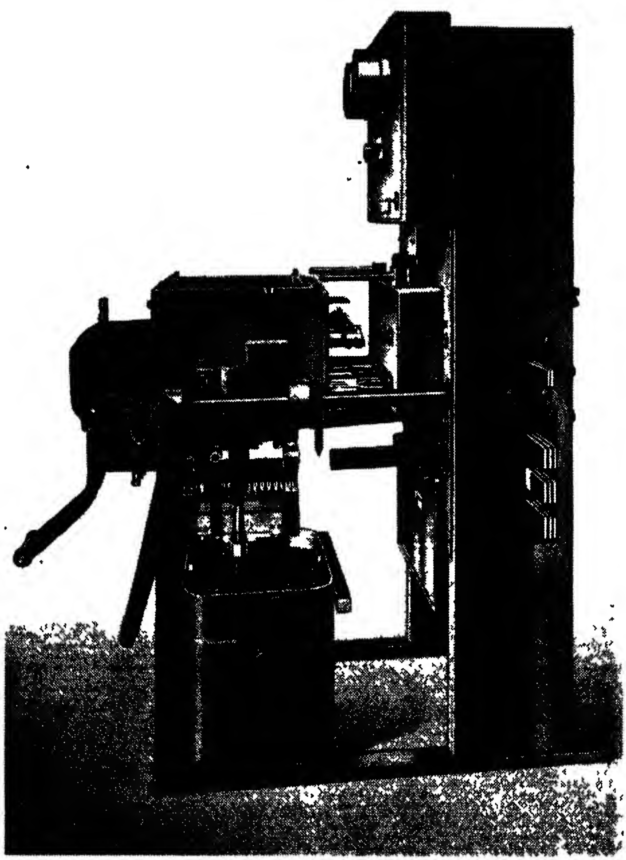


Fig. 11-2.—*Draw-out type switchgear unit with circuit-breaker tank lowered. 2 000 ampere rating (Johnson & Phillips Ltd.).*

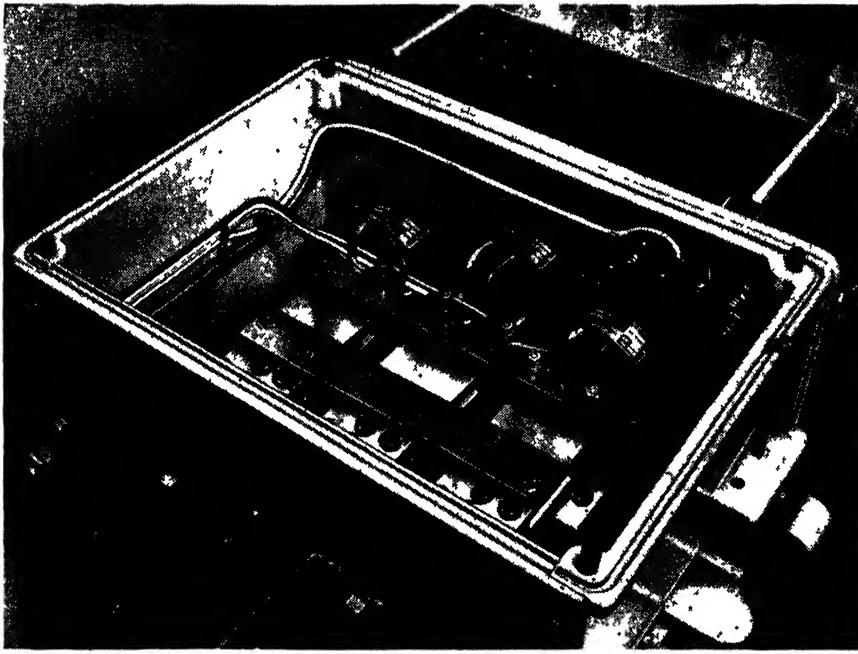


FIG. 11-3 —*Interior view of 2 000 ampere industrial circuit-breaker showing one method of mounting current transformers (Johnson & Phillips Ltd).*

In gear of this type, automatic shutters over the busbar and feeder line contacts are not normal, but a hinged cover is provided for hand operation if it is required to protect the contact orifices at any time, e.g. if a circuit-breaker is completely removed from its slide rails Provision for earthing (through the circuit-breaker) can be made in various ways, one of these being shown in Fig 11-4 where, with extended slide rails, an earthing device is fitted on these rails between the circuit-breaker and the pedestal When plugged into position, one side of the circuit-breaker is connected to the fixed isolating contacts and the other side directly to earth via the substation earth bar.

The pedestal which carries the circuit-breaker slide rails is constructed in the form of a sheet metal cubicle of simple design and this is arranged to house the busbar system, connections, fixed isolating contacts, current transformers and cable boxes as shown in Fig. 11-5. This unit construction facilitates extension should this be necessary later.

Some of the designs of oil circuit-breaker used in this type of gear are noted in Chapter VI.

Further examples of industrial switchboards of this general type are shown in Figs. 11-6, 11-7 and 11-8.

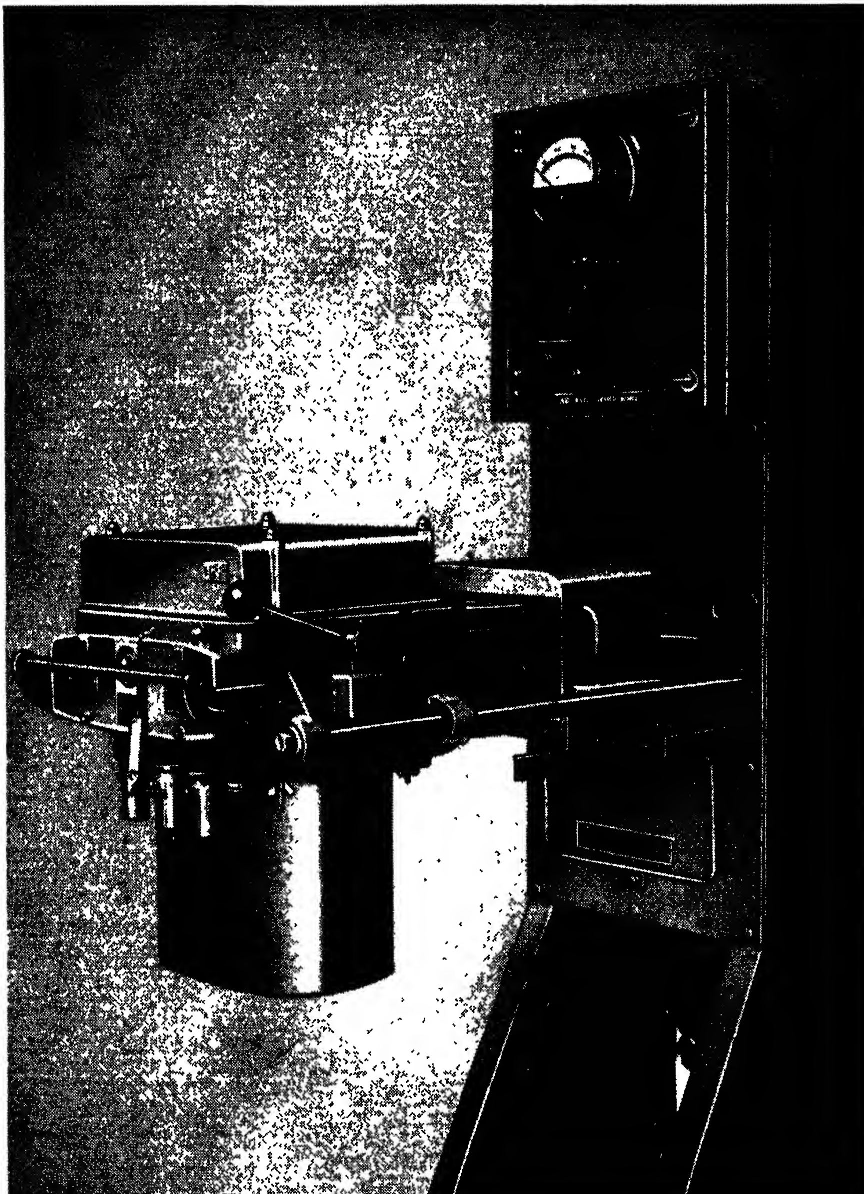


FIG. 11-4.—*Industrial oil circuit-breaker in isolated position and with earthing device fitted on slide rails (Johnson & Phillips Ltd.).*

FIG 11-5 —*Rear view of industrial type switchboard with covers removed to show busbars, connections, cable boxes, etc. (Johnson & Phillips Ltd.).*

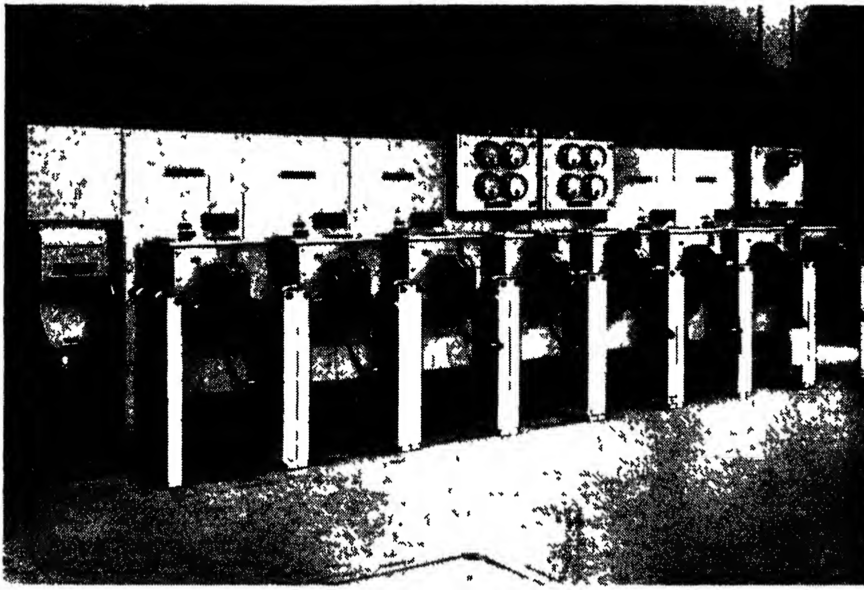


FIG. 11-6 — *Industrial switchboard of high current rating (Johnson & Phillips Ltd.)*

FIG. 11-7.—*Large industrial switchboard comprising incoming and bus section circuit-breakers (centre) and feeders disposed on either side. Note relay protection on feeder circuits (Johnson & Phillips Ltd.).*

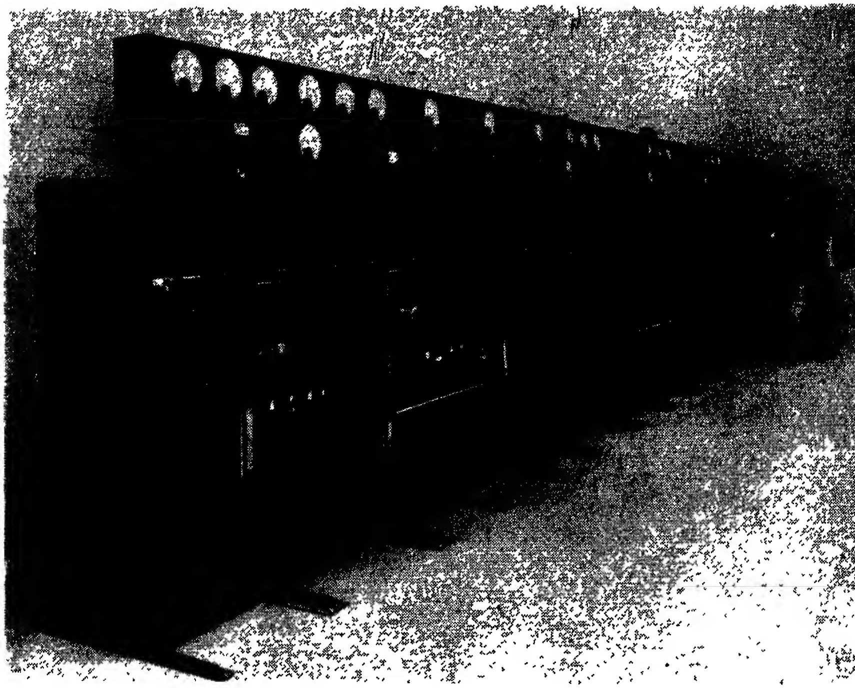
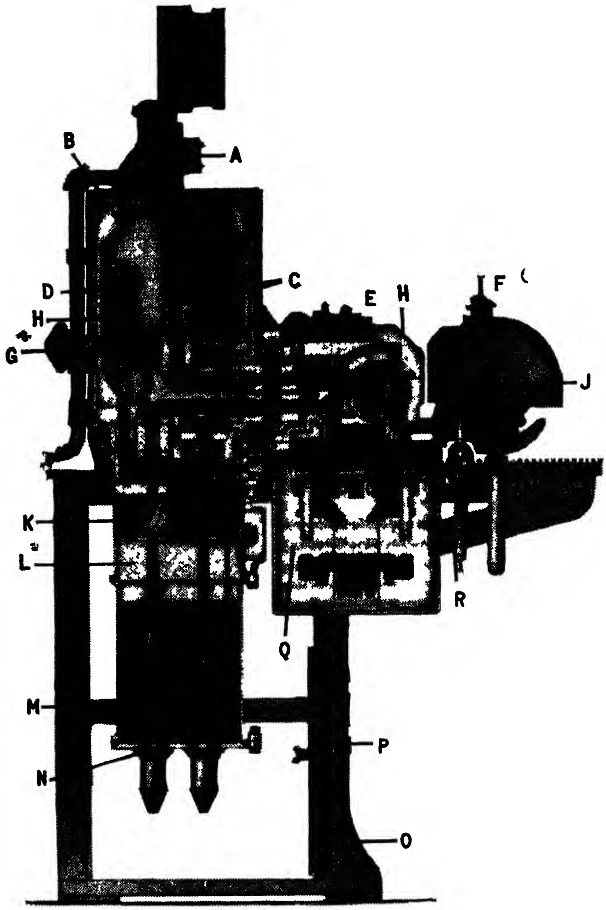


FIG. 11-8.—*Industrial switchboard of mixed current ratings (Associated Electrical Industries Ltd.).*

In the previous chapter we have noted a class of high-voltage switchgear in which the circuit-breaker is withdrawn horizontally on two side frames by means of rack and pinion. This principle is also used in a range of medium voltage switchgear for normal current ratings in the range 1 000-3 000 amperes, but whereas in the high-voltage type the busbars are compound filled, here they are air-insulated. The detail design of this type of unit will be clear from Fig. 11-9 and its appearance in the switchboard form from Fig. 11-10.

In Chapter VI note has been taken of the use of laminated brush type contacts (main) with spring-loaded butt type arcing contacts. It will be seen from Fig. 11-9 that here, again, the main contacts are similar, but the arcing contacts in this case are of the wedge and finger type.

For some applications where the normal currents are high, fixed cubicle type gear is often used, but as indicated in Chapter X, this does not lend itself readily to the application of the safety interlocks, complications arising due to (a) the multiplicity of access doors enclosing the separate compartments, and (b) the use of separate hand-operated isolating switches leads to



A —MEDIUM-VOLTAGE FUSES.
B —BUSBAR-CHAMBER (AIR-INSULATED).
C —MAIN BUSBARS.
D —NEUTRAL BUSBAR.
E —LOCKING-OFF DOOR
F.—ON AND OFF INDICATOR.
G —VENT-HEADER
H.—VENT-PIPE
J.—DIRECT-OPERATED CONTROL-MECHANISM.
K.—CURRENT-TRANSFORMERS.
L.—CURRENT-TRANSFORMER CHAMBER (AIR-INSULATED).
M.—CABLE-BOX
N.—INSULATED GLANDS
O.—FRAME-STANDARD
P.—RELAY-FRAME.
Q.—CIRCUIT-BREAKER
R.—CIRCUIT-BREAKER RACKING-HANDLE.

FIG. 11-9.—*Cross-section through 660 volt draw-out metalclad circuit-breaker unit (A. Reyrolle & Co. Ltd.).*

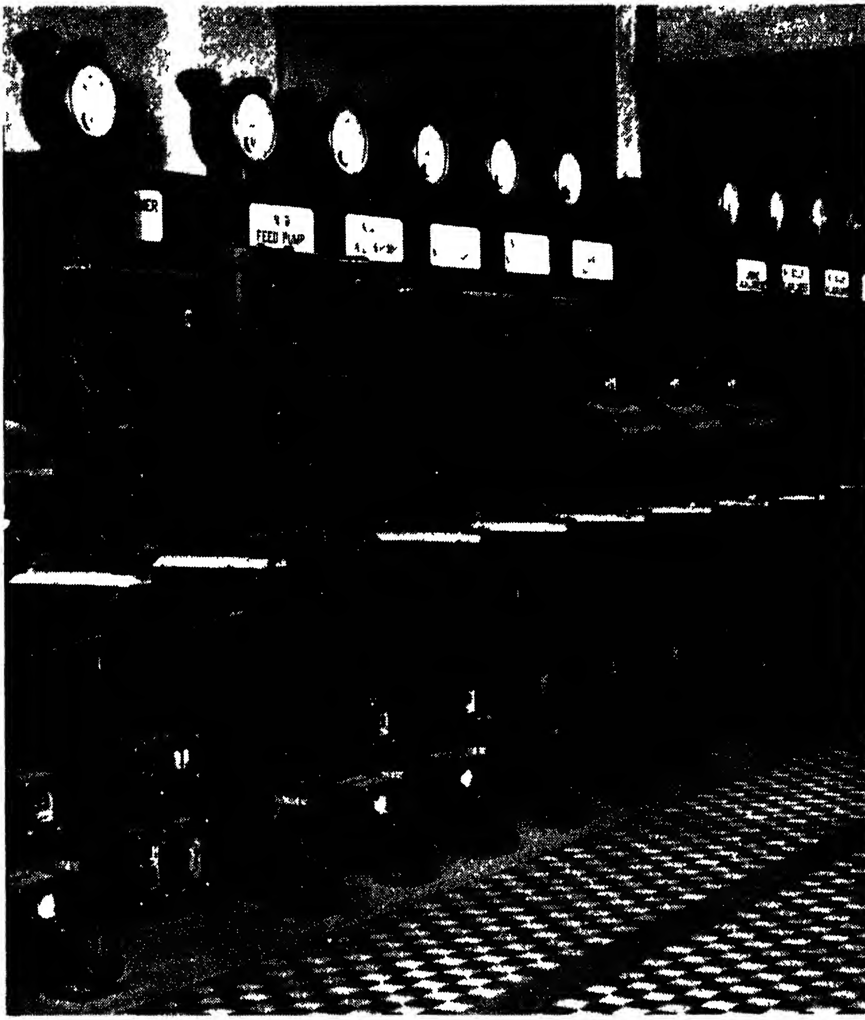


FIG. 11-10.—*Part of a switchboard of units as Fig. 11-9. Some closing mechanisms are of the solenoid type and others direct hand (A. Reyrolle & Co. Ltd.).*

inconvenience; where double isolation is essential the two isolators may be located at opposite points in the cubicle, thus adding to the complications.

An example of a switchboard of fixed cubicles is shown in Fig. 11-11, while Fig. 11-12 shows a cubicle in which is installed a 3 000 ampere oil

circuit-breaker. It is of interest to note that to assist in closing this heavy current circuit-breaker, an extremely long handle is fitted to the operating mechanism.

The growing popularity of air-break circuit-breakers for use on medium voltages at the higher breaking capacities has been noted in Chapter IX and their use in industrial and power station auxiliary switchboards has produced a variety of cubicle arrangements in single and double tier formations.

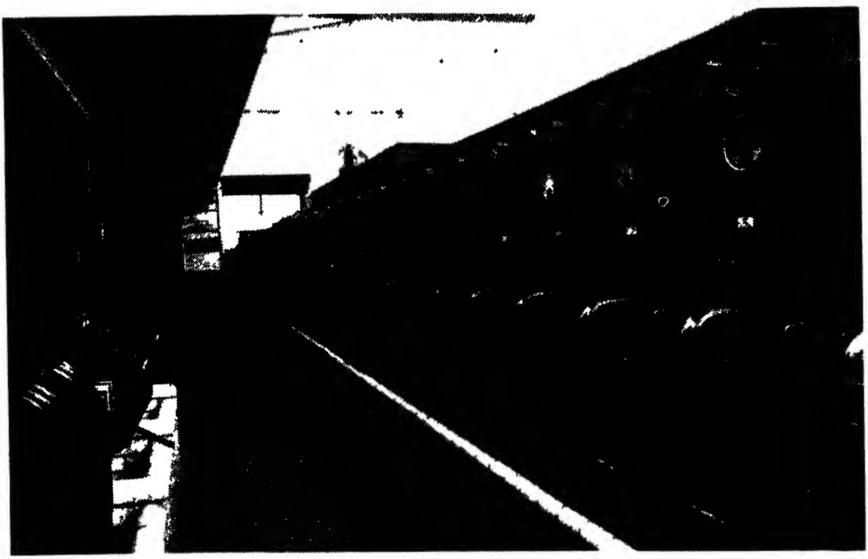


FIG. 11-11.—*Cubicle type medium-voltage substation switchboard (Johnson & Phillips Ltd.).*

An extremely clean frontal appearance has been achieved while retaining all the advantages of withdrawable circuit-breakers and in some designs the circuit-breaker operating mechanism is behind a door or front cover and a detachable handle is used through slots in an escutcheon plate to both close the breaker and to isolate it by withdrawal.

One such switchboard is shown in Fig. 11-13, noting that the two units in the centre are 3 000 ampere off-load incoming switches, while the circuit-breaker feeders are in double tier. In its normal isolated position the circuit-breaker is still within the cubicle but for inspection and maintenance it can, after opening the door, be racked further forward on extensible rails as shown in Fig. 11-14.

If, for any reason, a circuit-breaker must be completely removed from a cubicle, the use of a handling truck enables this to be done.

Switchgear units employing air-break circuit-breakers can readily be lined up with modern forms of fuse-switch cubicles and multi-motor con-

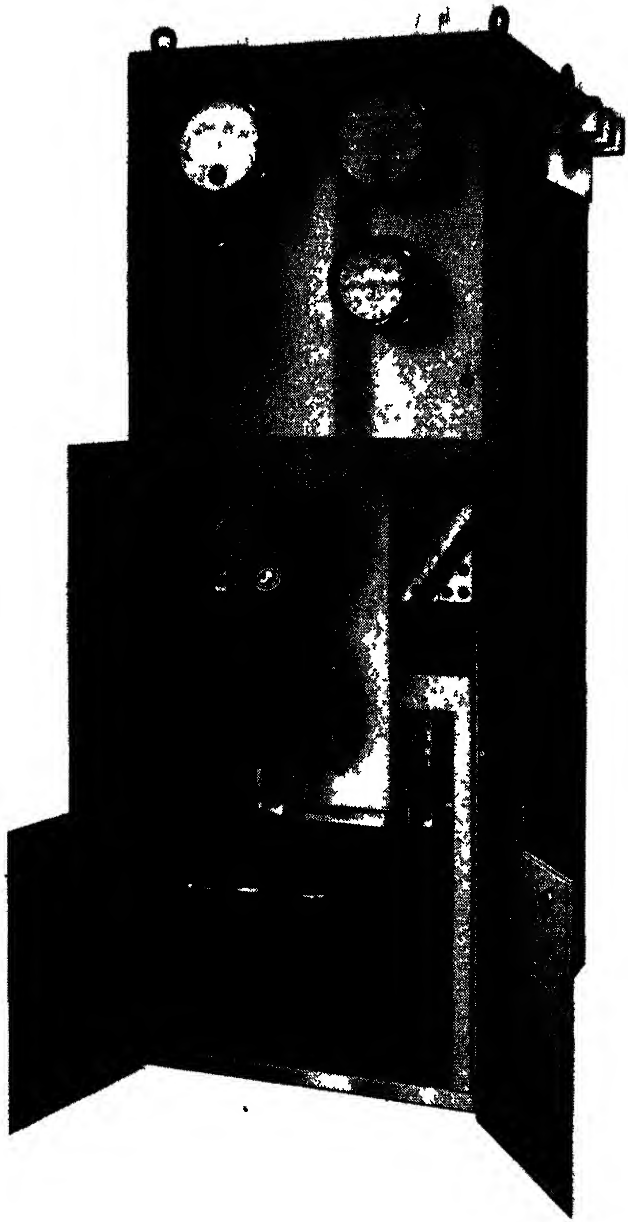


FIG. 11-12.—*Industrial type cubicle with 3 000 ampere oil circuit-breaker, tank lowered (Johnson & Phillips Ltd).*

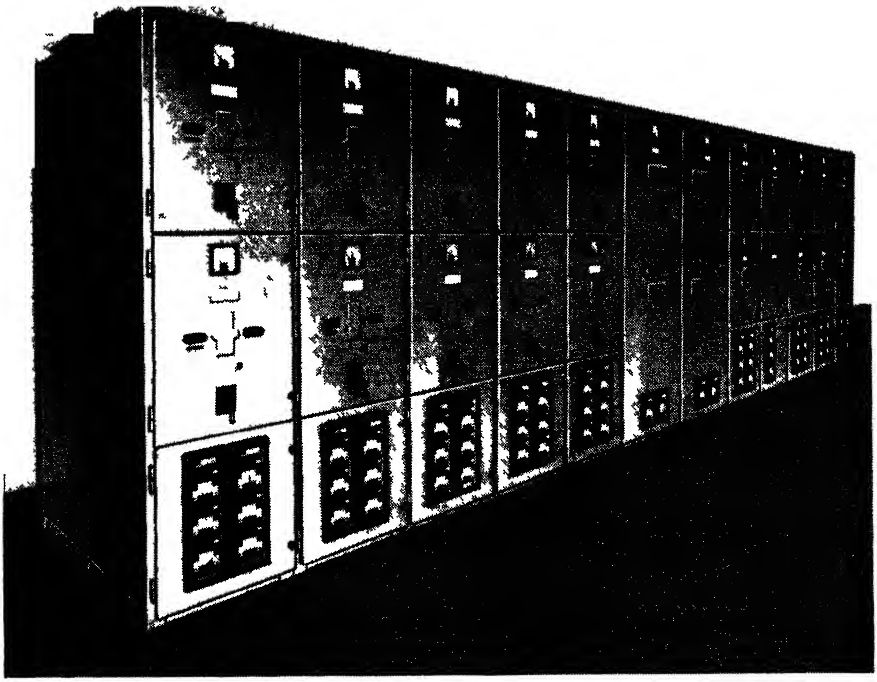


FIG 11 13—*Medium voltage switchboard using air-break circuit breakers* (*The English Electric Co Ltd*)

tactor starters One example is shown in Fig 11 15 where circuit breakers in double tier are lined up with fuse-switches and off load isolators

Single and double tier formation is also employed in the design shown in Fig 11-16, single tier being used for units of 2 400 ampere rating as seen in Fig 11-17

A design in which single tier formation only is employed is shown in Fig. 11-18, covering a normal current range of 1 200-2 400 amperes

A typical 1 200 ampere unit with the circuit-breaker withdrawn completely from its housing on a handling truck is shown in Fig 11-19

An interesting development in indoor medium-voltage switchgear is one in which an air-cooled power transformer is combined in a self-contained unit along with the necessary m v switchgear Such an arrangement is seen in Fig 11-20 where the doors of the transformer compartment are open to show the dry-type transformer and the busbar connections leading to the switchgear section

In this design, transformers up to 1 000 kVA can be accommodated for primary voltages of 6 6 and 11 kV The switchgear may consist of air-break circuit-breakers, fuse-switch units and off-load isolators in varied combinations to suit the application

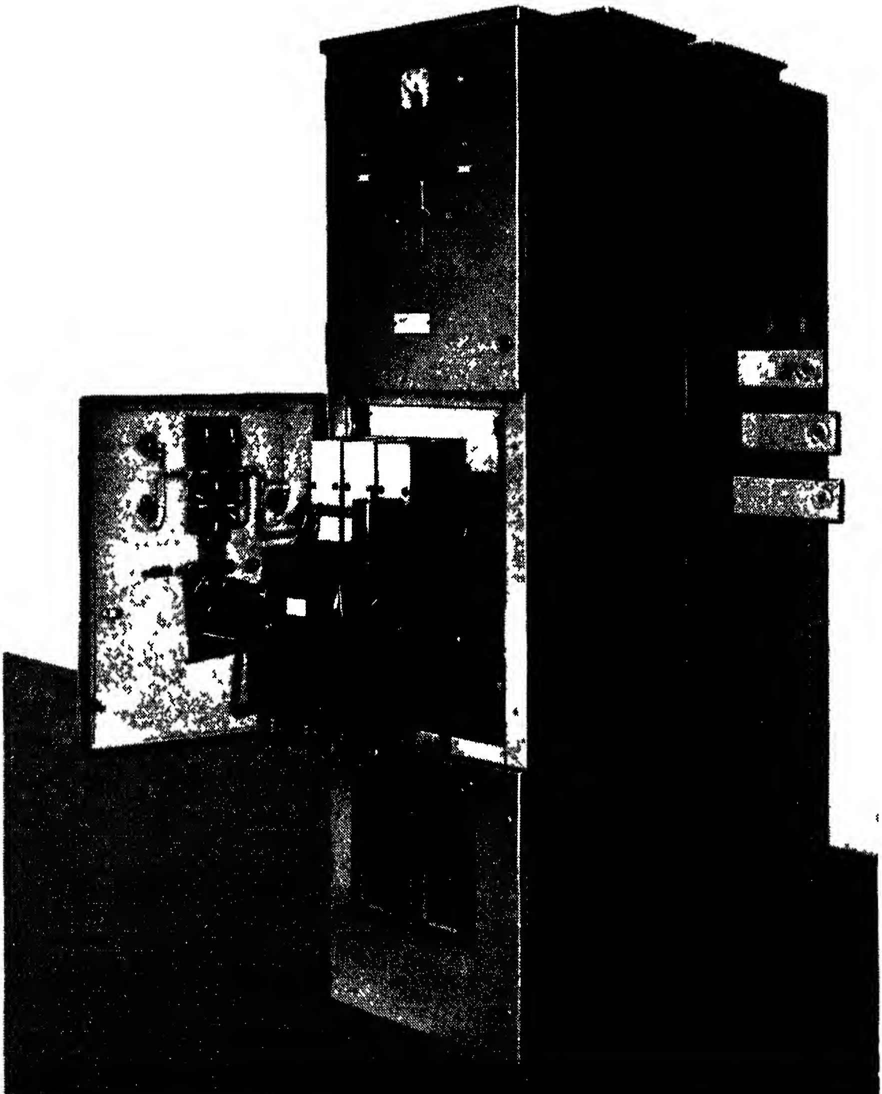


FIG. 11-14.—*One unit of a double tier cubicle with circuit-breaker fully withdrawn for inspection (The English Electric Co. Ltd.).*

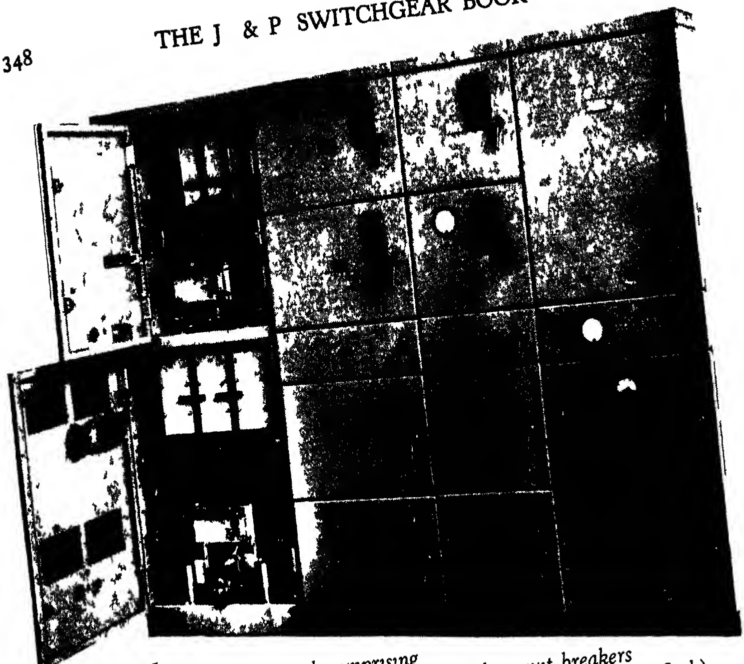


FIG 11-15
Medium-voltage switchboard comprising one 2 000 ampere and one 800 ampere air-break circuit-breakers along with fuse-switches and off-load isolators (General Electric Co Ltd).

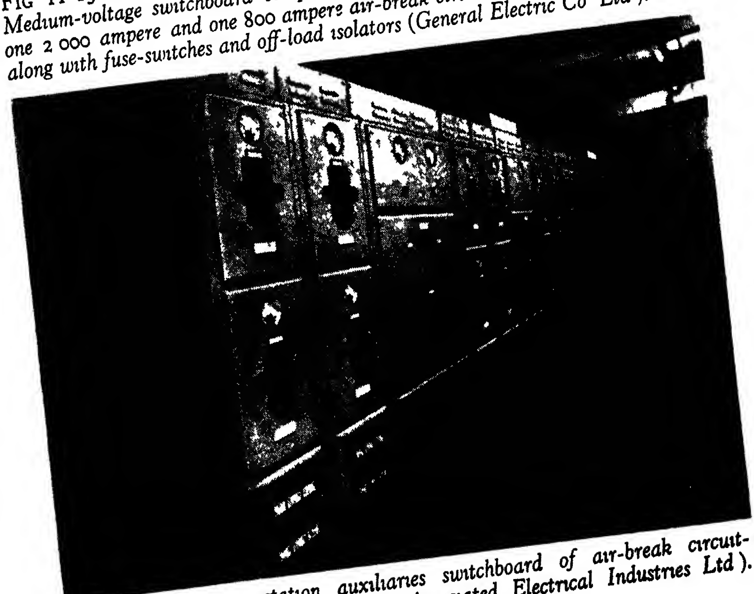


FIG 11-16.—Power station auxiliaries switchboard of air-break circuit-breakers in single and double tier (Associated Electrical Industries Ltd).

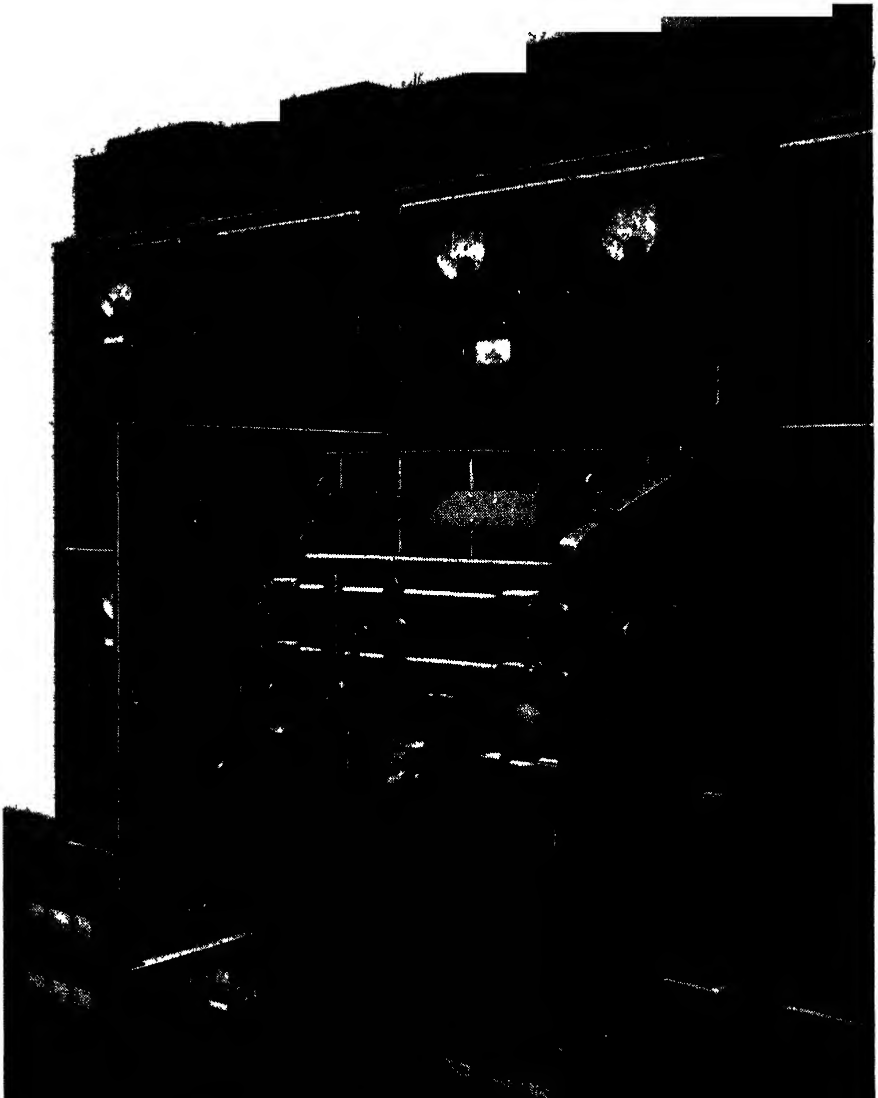


FIG 11-17—2 400 *ampere air-break circuit-breaker in withdrawn (maintenance) position (Associated Electrical Industries Ltd.).*

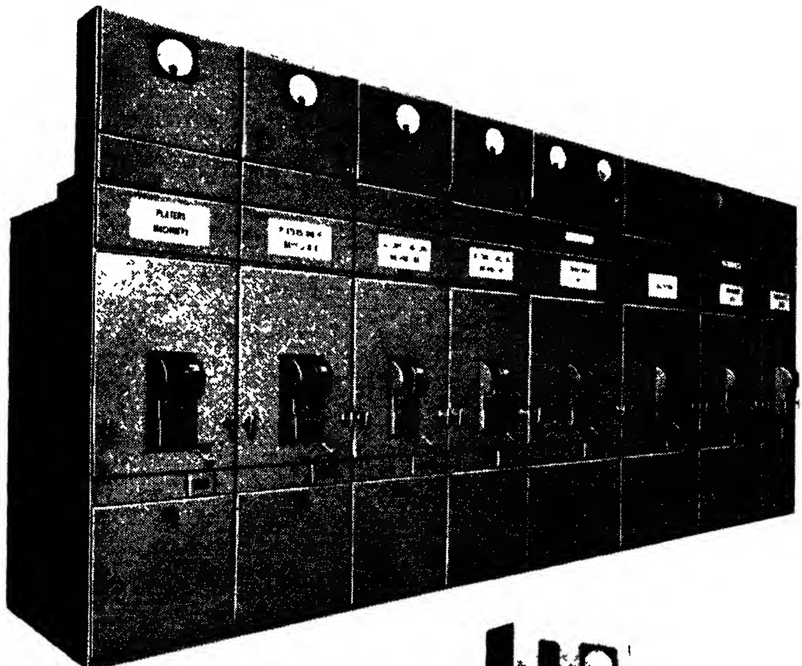


FIG. 11-18
Medium-voltage switchboard of air-break circuit-breakers (A. Reyrolle & Co. Ltd.)

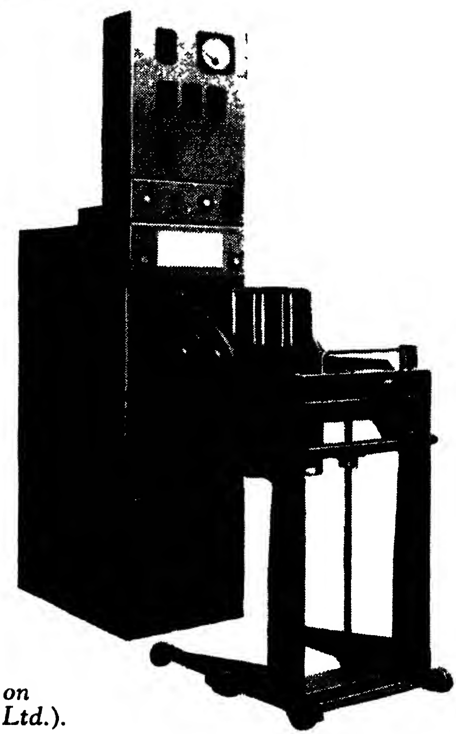


FIG. 11-19
1 200 ampere air-break circuit-breaker withdrawn from its housing on handling truck (A. Reyrolle & Co. Ltd.).

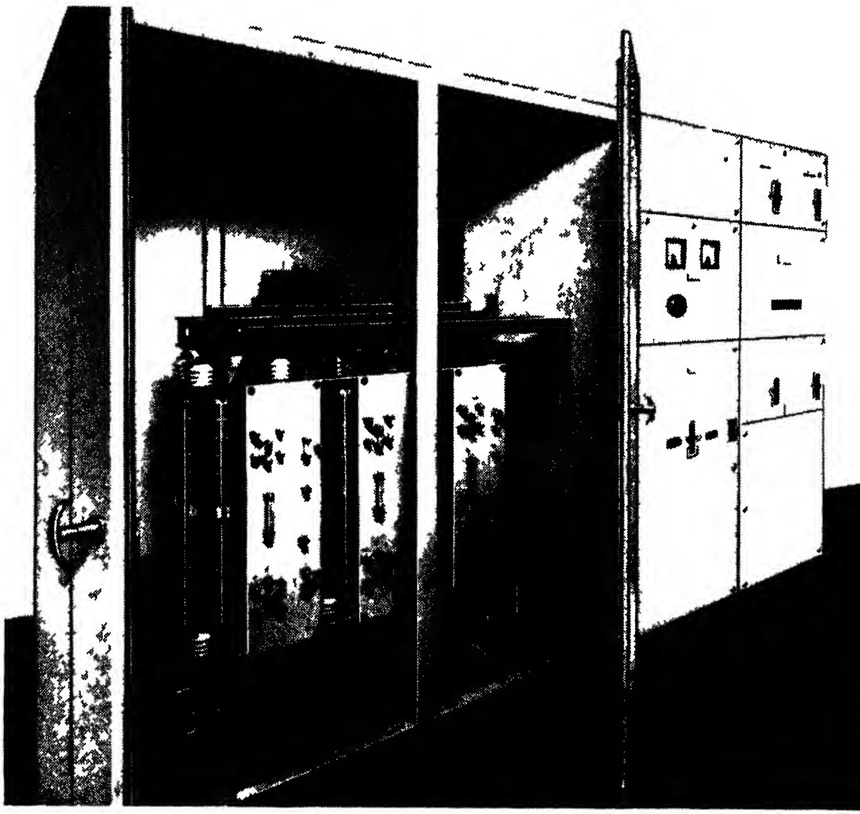


FIG 11 20 — *Indoor "packaged" substation comprising a dry-type, air-cooled power transformer and medium-voltage switchgear (The English Electric Co Ltd)*

CHAPTER XII

M.V. H.R.C. FUSES AND THEIR APPLICATION

CHAPTER XII

M.V. H.R.C. FUSES AND THEIR APPLICATION

As a circuit interrupting device under conditions of short-circuit, the modern h.r.c. fuse is in many ways superior to the oil or air-break circuit-breaker. In the medium voltage range voltages, 400-600 volts, it can successfully interrupt fault currents (prospective) up to the present recognised limit of 46 000 amperes symmetrical (B.S. 88 : 1952)* and there are records of successful interruption up to 200 kA r.m.s. symmetrical for the American market, in accordance with N.E.M.A. standards. Fuses for this market are now being manufactured in this country (English Electric), and have been tested and certified to this very high value of fault current.

Its superiority over other interrupting devices lies mainly in (a) its ability to limit the fault current to a value less than the prospective peak in the first half-cycle of short-circuit, (b) in consequence of (a) the fault is interrupted in less than one half-cycle, and (c) it does all this in a bulk of a few cubic inches and at relatively low cost. Whilst these attributes give it superiority as a short-circuit device, it should be considered as complementary to the circuit-breaker in situations where overload or some other form of protection is of equal importance. The use of one or the other must also depend on considerations related to the system as a whole.

The fuse, by comparison with the circuit-breaker, suffers the disadvantage that replacement is necessary after operation. This is offset in situations where the fault level is high by the fact that the physical size of the fuse, and therefore its cost, is directly proportional to its current rating, whereas the dimensions of the circuit-breaker are determined by its breaking capacity irrespective of current rating. The fuse, being a thermal device, generates more heat than the current-carrying parts of a circuit-breaker of equivalent normal current rating and the effect of temperature rise of the fuse must be taken into account in relation to associated apparatus. Fuse-links are listed in B.S. 88 up to 1 200 amperes and are in common use up to this rating.

The excellence of present designs is due to the extensive research and development which has been sustained since about 1926 when, good as fuses were at that time, it was realised that the rapid increase in fault power would demand higher breaking capacity in protective devices than then existed. About that time too, improved facilities for high-power testing under controlled short-circuit conditions were becoming available (see Chapter V) to take the place of large secondary batteries which had been a recognised source of power for tests at high current values. A paper by Grant (1926) analysed the state of the art at that time and outlined many of the problems demanding investigation and it can be said with fairness that the fuse of today embodies the results of such investigation.

* *Under revision. Any new issue of B.S.* 88 *should be studied in relation to the data given in this chapter.*

It is not within the scope of this book to discuss in any detail the process of circuit-breaking in an h.r.c. fuse except only so far as it is necessary to appreciate this process as it affects the application of fuses. It is of interest however to note that basically all h.r.c. fuses comprise a ceramic body to contain one or more specially designed fuse elements, these being connected

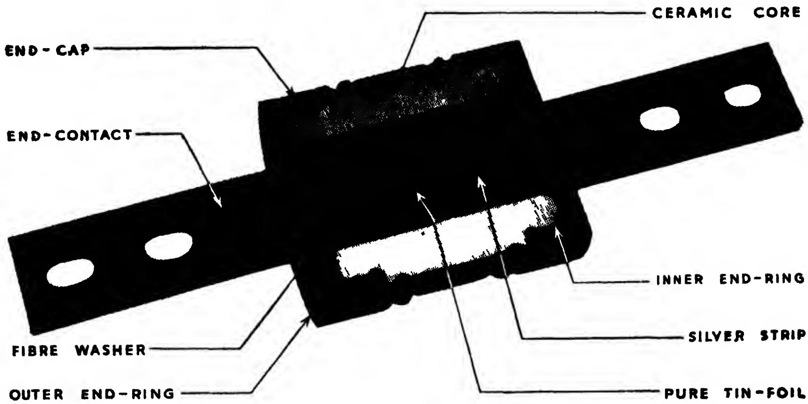


FIG. 12-1.—*Sectional view of typical Class GP Type 5 cartridge fuse-link (A. Reyrolle and Co. Ltd.).*

to metal end caps which serve also to seal the body after it is filled with powder, usually quartz. Typical of this construction is the fuse-link shown in the cut-away illustration Fig. 12-1, while in Fig. 12-2 is seen an external view of another fuse-link.

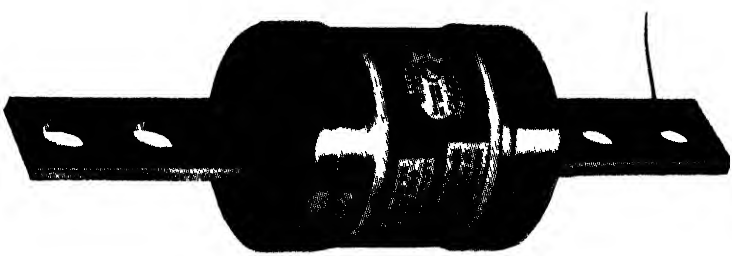


FIG. 12-2.—*Cartridge fuse-link Category AC5 (The English Electric Co. Ltd.).*

The elements, as noted later, are designed such that melting will occur at a point or points depending on the configuration or on purposely introduced low-melting-point regions, the time required for melting depending on the magnitude of the current. Vaporisation of the metallic element occurs on melting and there is fusion between the metallic vapour and the filling powder leading to rapid arc extinction. This chemical reaction produces a substance of high resistance which becomes an insulator as the current is interrupted.

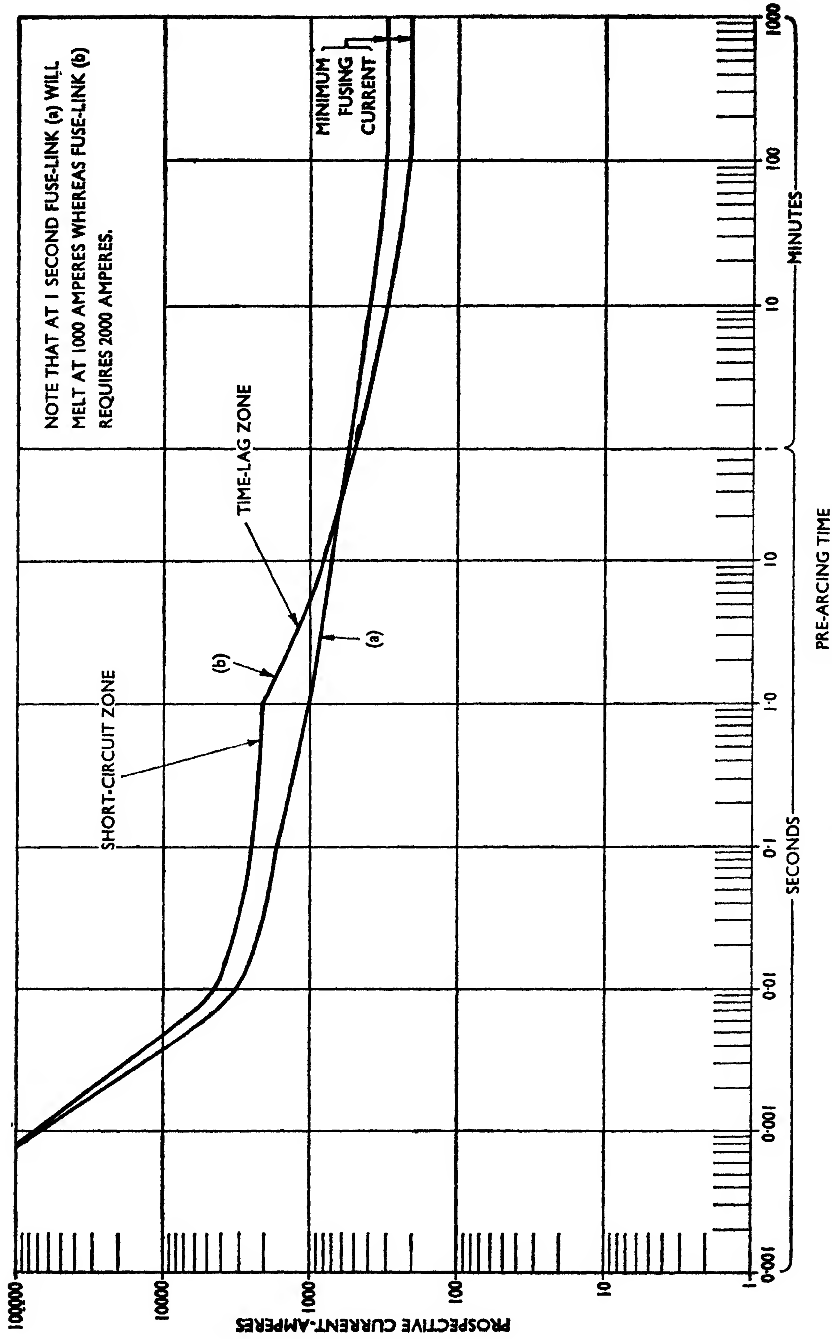


FIG. 12-3.—*Showing approximate characteristics of single and dual element fuse-links of equal normal current rating.*

In the application of h.r.c. fuses, there are three broad requirements to be studied:—

1. *Protection* for apparatus and conductors against the possibility of damage due to the passage of current greater than normal. Such damage may be thermal or mechanical or both.
2. *Co-ordination* between fuses and other apparatus which can be tripped open by other overcurrent devices, e.g. a circuit-breaker or contactor.
3. *Discrimination* between fuses in series.

For a study of protection, it is at once important to note the existence of fuses having entirely different time/current characteristics. Typical curves to illustrate the difference between two particular designs are given in Fig. 12-3 where the curve at (a) is representative of fuse-links using a silver wire or strip element while the curve at (b) shows the characteristic of a fuse-link employing a dual element which has two zones of operation, one for the clearance of high-current values, the other a time-lag zone for moderate over-currents.

The first of these types complies with B.S. 88 : 1952 for Class Q fuse-links which are intended for use when it is not required to have a close degree of protection against relatively small overcurrents and having a fusing factor* not exceeding 1·75. The second type is representative of Class P fuse-links and these are intended for use where it is required to include protection against small but sustained overcurrents, the fusing factor being 1·25.

Curve (b) is important in the fact that there is discontinuity at the point of change-over from time-lag operation to the quick-acting (short-circuit) zone and this change is achieved in the design of the element which, as shown in Fig. 12-4, is in the form of dual elements.

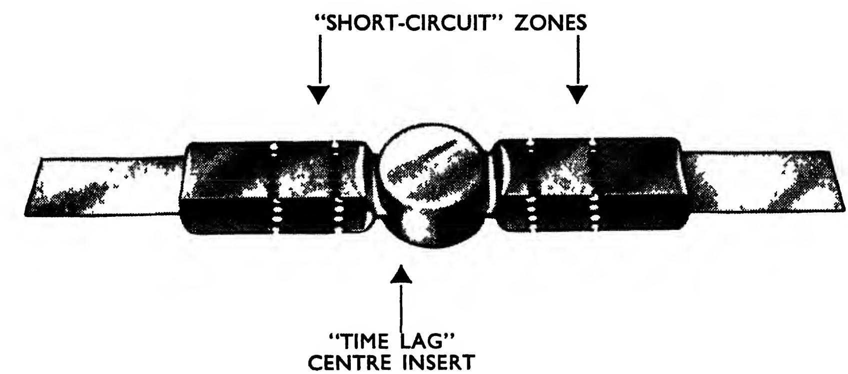


FIG. 12-4.—*Dual element of "Brilag" fuse-link (Parmiter, Hope & Sugden Ltd.).*

**The fusing factor of a fuse is the ratio, greater than unity, of the minimum fusing current to the current rating, namely—Fusing factor=* $\dfrac{\textit{minimum fusing current}}{\textit{current rating}}$

The two outer ends of this element comprise copper strips which are perforated to form a constriction for operation at the higher current values. Between them there is a time-lag insert which consists of a plug of low-melting-point alloy which melts at 180°C and it is this section which melts on sustained but small overcurrents.

The elements which produce curves similar to that at (a) are usually made of silver wire, or strip with a series of narrowings or necks, coupled with a plug of low-melting-point which alloys with the silver wire or strip when melting occurs. These designs may be seen as shown typically in Fig. 12-5, while Fig. 12-6 shows typical silver wire elements both before and after operation.

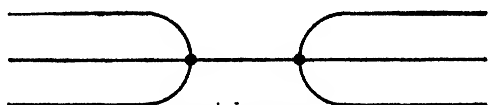


FIG. 12-5.—*Typical single elements*

In another design, fuses with either quick-acting or slow-acting characteristics are available where the characteristic time-current curve is continuous (as in (a) Fig. 12-3) in both types but the slow-acting characteristic curve is modified in its slope (for times greater than 1 second) to give longer pre-arcing times at the lower values of current. This change is obtained by the introduction of an alloying medium having a fusing temperature below that of silver. The difference between the element construction in these designs is shown in Fig. 12-7.

The arguments for and against the two sets of characteristics have been ventilated in some detail in a paper by Dean and the discussion on that paper. One argument by those who prefer the dual-element fuse-link is that the time-lag action permits the use of fuse-links having normal ratings nearer to the normal full load current of a motor than is possible with other types and that this is so even with direct-on-line started induction motors taking six to eight times full load current from the line at starting. Against this it is argued that by specification a contactor must itself be capable of breaking up to six or eight times the normal current rating of the contactor, i.e. the stalled current of the motor, and therefore should, in association with its overload device, be allowed to deal with overcurrents of these magnitudes. This aspect will be noted again under co-ordination.

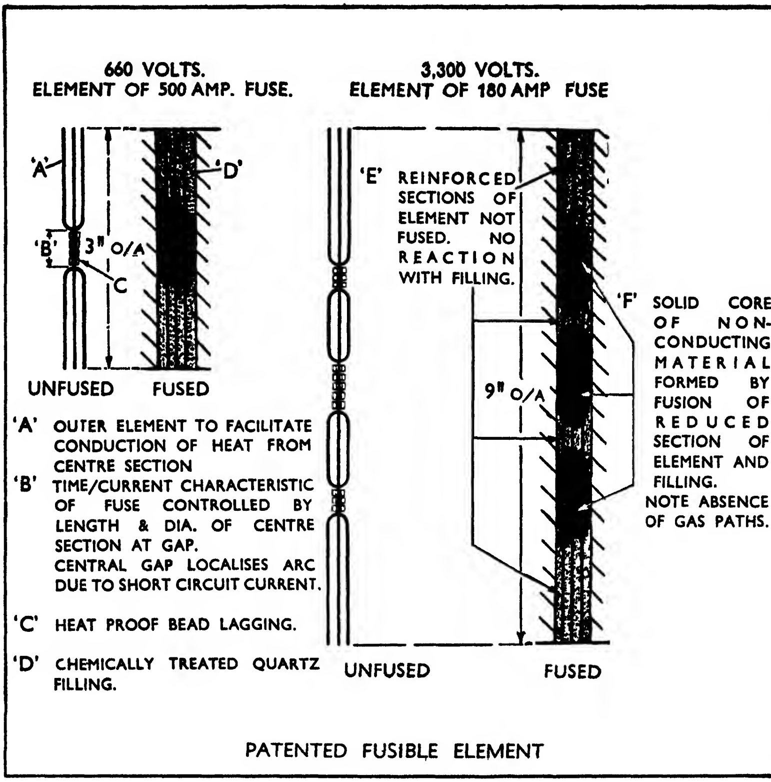


FIG. 12-6.—*Fusible element of high rupturing capacity fuse-links (The English Electric Co. Ltd.).*

In other circumstances, a fuse may be applied for the protection of a cable and while here there need not be a wide margin between the fuse-link rating and the rating of the cable (noting that the I.E.E. Wiring Regulations require the rating of the fuse-link to equal that of the cable except in a special case), the exponents of the dual-element fuse-link point out that here it is clearly preferable to have a fusing factor of 1·25 rather than 1·75, the former giving protection at 25 per cent overload, the latter at 75 per cent.

Whether h.r.c. fuse-links are of one type or the other, however, all exhibit at values of prospective current above a known minimum that most valuable characteristic known as "cut-off". This means that the short-circuit current is interrupted before it can reach the prospective value in the first half-cycle of short-circuit and is demonstrated in Fig. 12-8 from which it is seen that at (a) the rising current wave is stopped (element melts) and it dies away during the arcing period to zero at (b). The value at which "cut-off" occurs may vary as between designs and Fig. 12-9 shows the values for English Electric Type T fuse-links. "Cut-off" values vary firstly

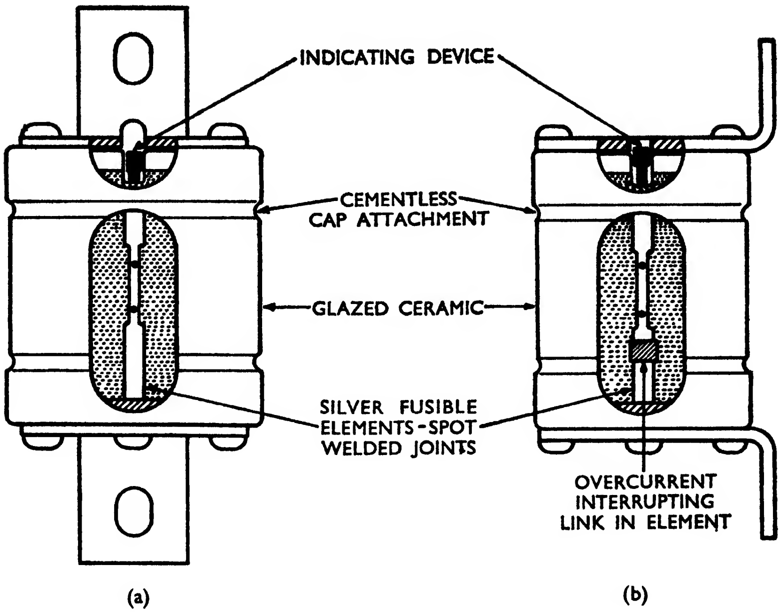


FIG. 12—7.—*H.R.C. fuse-links*

(*a*) *identically graded elements for Classes Q or R* (*b*) *graded and interrupting elements for Class P (EMP. Electric Ltd.).*

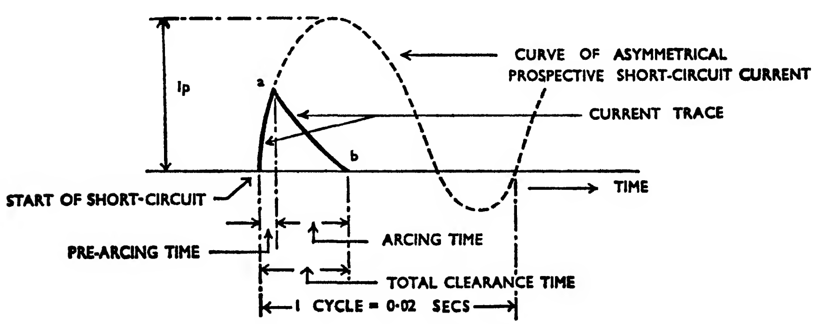
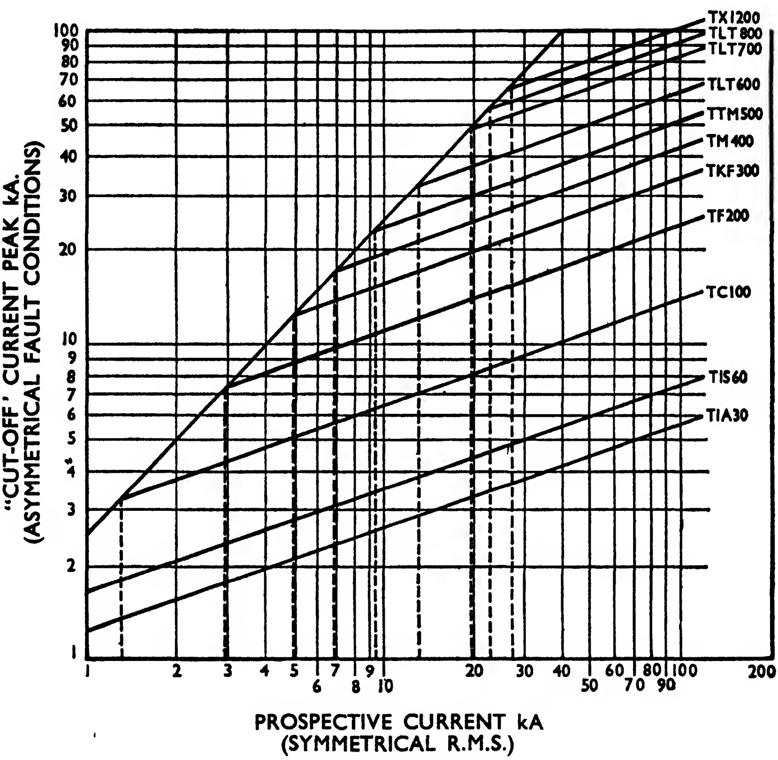


FIG. 12-8.—*Illustrating "cut-off" feature in h.r.c. fuses.*

in relation to the normal rating of the fuse-link, secondly in relation to the prospective value of the short-circuit current and thirdly to the degree of asymmetry. The curves in Fig. 12-9 assume maximum asymmetry.

It is important to note that the values of prospective current are symmetrical r.m.s. and in Chapters III and IV we have seen how to calculate these for any defined system. Thus, if we assume a fault value of 25 MVA at 440 volts equivalent to 33 000 amperes (symmetrical r.m.s.), then a 30 ampere fuse-link in that circuit would "cut-off" at approximately



NOTE: THE DOTTED VERTICAL LINES PROJECTED DOWN TO THE BASE SHOW, ON THE HORIZONTAL SCALE, THE VALUE OF PROSPECTIVE CURRENT (SYMMETRICAL R.M.S.) AT WHICH THE RESPECTIVE FUSE-LINKS BEGIN TO EXHIBIT "CUT-OFF"

FIG. 12-9.—*Curves showing "cut-off" currents for Type T fuse-links over a range of prospective fault currents based on fully asymmetrical conditions where the peak current is 2.55 times the r.m.s. symmetrical value, i.e. power factor 0.15 or less (The English Electric Co. Ltd.).*

3 900 amperes. Had no fuse been present then the peak current (Ip in Fig. 12-8) in at least one phase could reach 84 000 amperes. On the other hand,

TABLE 12 : 1

3-phase S.C. MVA	Prospective symm. r.m.s. amperes at 415 V	Fuse-link ratings (amps)									
		30	60	100	200	300	400	500	600	800	1 200
		Factors									
10	14 200	0·0064	0·011	0·04	0·12	0·23	0·35	0·51	0·85	1·0	1·0
15	21 000	0·0045	0·0068	0·023	0·068	0·14	0·21	0·314	0·49	1·0	1·0
20	28 000	0·0026	0·0047	0·016	0·047	0·095	0·143	0·21	0·31	0·71	1·0
25	35 000	0·002	0·0035	0·012	0·036	0·072	0·105	0·152	0·25	0·51	0·64
30	42 000	0·0015	0·0027	0·009	0·028	0·055	0·084	0·126	0·20	0·43	0·5
35	49 000	0·0013	0·0023	0·0077	0·023	0·045	0·07	0·011	0·16	0·34	0·41

This table shows the reduction in electromagnetic forces imposed on busbars and apparatus when a fuse is in circuit. For example, in a circuit with a fault level of 25 MVA, the forces with no fuse present would be 1·0 whereas with (say) 400 amp fuses in circuit, the forces would be 0·105 or only 10 per cent. With 800 ampere fuses, the forces are 0·51 or 51 per cent.

if the fuse-link had been rated 300 amperes then "cut-off" would not occur until 23 000 amperes or, going to the extreme, a 1 200 ampere fuse-link would be "cut-off" at about 70 000 amperes.

The real significance of "cut-off" will be better appreciated by noting the data given later in Chapter XIV (Busbars and Busbar Connections) concerning the electromagnetic and thermal effects on busbars and connections when these are carrying short-circuit current. It will be shown, for example, that the electromagnetic forces set up tending to distort the busbar or connection structure, are related to the *square* of the current value and this being so, the design problem is radically eased if the current concerned is, as noted earlier, the "cut-off" current of say 3 900 or 23 000 amperes instead of a possible peak value of 84 000 amperes. Even the worst condition of 70 000 amperes is an improvement.

Thus, it is shown that where fuses can be used to protect busbars in particular, and other connections and apparatus within the zone of protection, very considerable reductions are attained in the electromagnetic forces given in Table 14 : 5 in Chapter XIV and to emphasise this, Table 12 : 1 shows the multiplying factors which may be applied to arrive at the reduction to be expected. This table assumes maximum asymmetry and "cut-off" values from Fig. 12-9.

The thermal problem in relation to busbars and conductors is also eased, if not entirely eliminated, by the application of h.r.c. fuses as current limiting devices.

In Chapter XIV, details will be given showing how the cross-sectional area of copper and aluminium conductors may be determined to carry a given fault current for a specified time and temperature rise above a given initial temperature. From that data it is possible to produce Table 12 : 2 showing the approximate section of copper conductor necessary for various values of current and time periods.

TABLE 12 : 2

S.C. MVA	Symm. r.m.s. amperes at 415 V	Approximate cross-sectional area of copper conductor in sq. in. assuming a maximum permissible temperature rise of 100°C from an initial temperature of 20°C			
		0·5 sec.	1·0 sec.	2·0 sec.	3·0 sec.
10	14 200	0·14	0·19	0·27	0·33
15	21 000	0·22	0·28	0·39	0·48
20	28 000	0·28	0·37	0·52	0·64
25	35 000	0·36	0·46	0·65	0·80
30	42 000	0·47	0·61	0·86	1·0
35	49 000	0·50	0·65	0·92	1·1

This table shows that if, for example, it is required that busbars and conductors (and indeed certain items of apparatus such as isolating switches) should be suitable for a fault value of 35 MVA for one second, then, if the temperature rise limit is 100°C, above 20°C initial, the busbars and conductors (and isolating switch blades) must have a cross-sectional area of 0·65 sq. in. To meet this (nearly) a section of 2½ in. by ¼ in. may be acceptable, a section

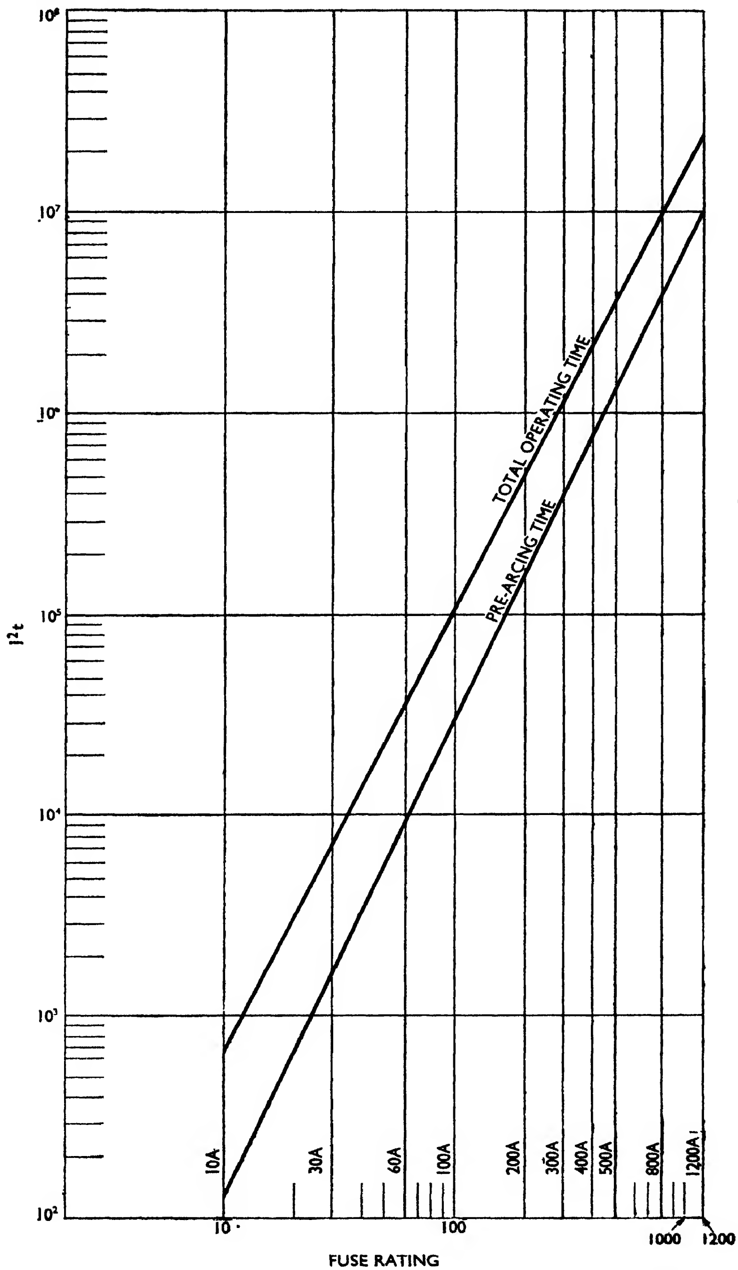


FIG. 12-10.—*I^2t characteristics for Type T fuse-links for general industrial use (The English Electric Co. Ltd.).*

which will carry continuously 1 000 amperes or more. But this could be quite unnecessary for normal conditions which might be satisfied with conductors good for 200 amperes and it is an interesting exercise to study how a set of, say, 400 ampere fuse-links on the incoming side make it possible to use the smaller section conductors.

In a paper by Jacks it is pointed out that when the *pre-arcing time* of a fuse is less than 0·02 seconds, the *total operating time* is extremely difficult to determine. It is therefore suggested that the criterion for such short times should be the values representing the energy admitted during operation and expressed in "amperes^2 seconds" or more briefly I^2t. A range of such values is given in Fig. 12-10 for both total operating times and pre-arcing times. Here we shall be concerned only with the curve for total times, that for pre-arcing times being considered later when discussing discrimination.

The following formula, from the book "Copper for Busbars", shows how the time "t" in seconds can be determined for the temperature of a copper conductor to rise θ°C above an ambient temperature of 30°C when carrying a short-circuit current of I amperes:—

$$t=2{\cdot}13\left(\frac{A}{I}\right)^2\left[\sqrt{(1+0{\cdot}00756\ \theta)}-1\right].10^{10}$$

where A is the cross-sectional area in square inches.

This formula can be re-arranged to obtain the area necessary, using I^2t values, thus—

$$A=\sqrt{\frac{I^2t}{2{\cdot}13.[\sqrt{(1+0{\cdot}00756\ \theta)}-1].10^{10}}}$$

From Fig. 12-10 for a 400 ampere fuse it is seen that the I^2t value is $2{\cdot}3.10^6$ and if the permissible temperature rise is 100°C then:—

$$A=\sqrt{\frac{2{\cdot}3.10^6}{2{\cdot}13.[\sqrt{(1+0{\cdot}00756.100)}-1].10^{10}}}$$

$$=\sqrt{\frac{2{\cdot}3.10^6}{0{\cdot}7.10^{10}}}=0{\cdot}018 \text{ sq. in.}$$

To carry a normal full load current of 200 amperes a cross-sectional area of 0·125 sq. in. (1 in. by ⅛ in.) would be adequate, so that no thermal problem remains when h.r.c. fuses can be provided in front of the equipment. The effect is of course more pronounced for systems of low normal current values and using fuse-links of low rating, but even had the fuse rating in the example used been 800 amperes with an I^2t value of 1.10^7, the thermal problem would not arise, a conductor area of 0·0377 sq. in. sufficing.

Finally on protection it should be noted that the problem of short-time ratings for cables is very considerably eased when these are protected by h.r.c. fuses as again the current to be carried is the "cut-off" current and that only for the short time required by the fuse to interrupt the fault. The question of short-time ratings for cables has been noted in Chapter III.

Co-ordination of fuses with other apparatus which has its own automatic devices for tripping open on overcurrent involves a study of two time/current characteristic curves, i.e. that of the fuse and that of the overcurrent device,

usually thermal or magnetic and sometimes a relay which is current transformer operated.

The fuse and the overcurrent device in such circumstances must share the duty of protecting a motor or cable in such a way that the breaking capacity of the automatic device (circuit-breaker, load breaking switch, or contactor), will be fully utilised. This is essential in that it is naturally much more convenient to reclose a circuit-breaker or contactor than to replace a fuse and the latter should only operate under conditions outside the ability of the other device. This leads therefore to a study of two characteristics superimposed and it will be found that a point of cross-over occurs.

One example of this is shown in Fig. 12-11 where the curves appropriate to a 60 ampere trip coil are shown to cross the curves of three fuse ratings. Thus, the coil set to trip at 200 per cent crosses the 200 ampere fuse curve at about 700 amperes and at values below this current, the fuse is slower in operation than the overcurrent device and therefore any overcurrent up to

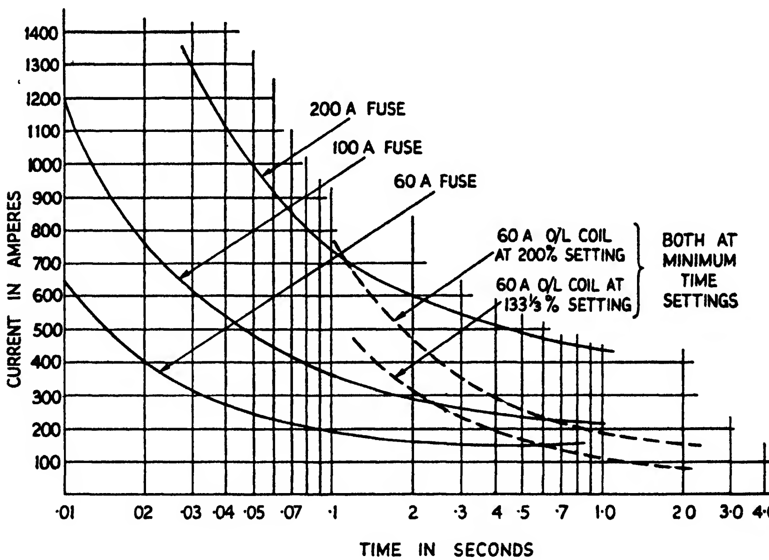


FIG. 12-11.—*Illustrating "cross-over" feature in characteristic time/current curves of direct-acting trip coils and* h.r.c. *fuse-links.*

at least 700 amperes must be cleared by the device associated with the trip coils. This feature is of particular importance when fuses are associated with contactors used for motor starting. Here, the fuse rating will be chosen to ensure that it will *not* operate during the starting period of the motor when a current up to six or eight times full load current is taken from the line for a short period of time. The overcurrent device on the starter will have a special characteristic to take care of the same condition so that the superimposed curves will now appear as shown typically in Fig. 12-12.

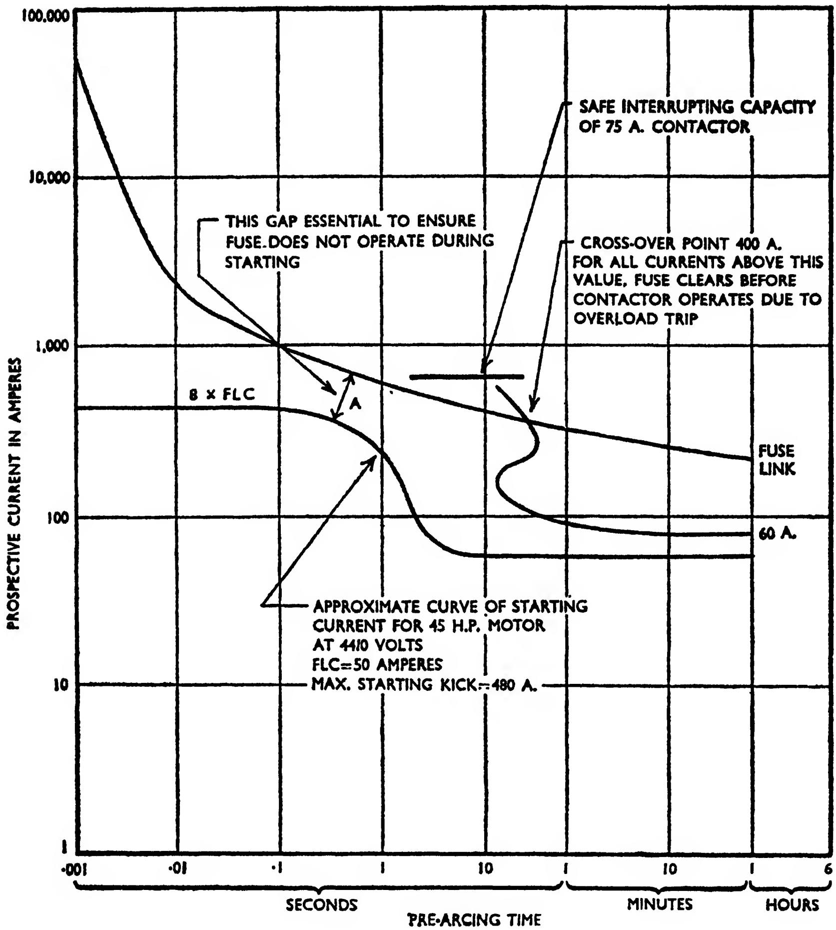


FIG. 12-12.—*Illustrating co-ordination between h.r.c. fuses and magnetic overload trip, motor starting current and safe value for contactor.* (*The Belmos Co. Ltd.*).

In applications such as these, an important feature is that the fuse is providing back-up protection for another circuit-interrupting device which has only limited ability but allowing that ability to be used to the full so that unnecessary fuse operation is avoided.

It is of course possible that a fault may exist on a system at the moment this other device is closed so that it must have the ability to "make" onto currents equal to the maximum value of "cut-off" current of the fuse. To ensure this may mean the selection of a fuse rating lower than would be chosen by other considerations.

To some extent the question of co-ordination just considered can be regarded equally as a problem of discrimination and is indeed included under this heading in B.S. 88 : 1952 (Appendix H), but here it will be assumed that the major problem of discrimination is that which involves two or more sets of fuses in series. This subject has been dealt with rather fully in the paper by Jacks in which he discusses not only the aspect of discrimination as may be determined from time/current characteristic curves, but also from the point of view of system layout, unequal loading causing one fuse to be running warm and the other cool, and the effect of installation abuses.

The simplest case for discrimination concerns two fuses in series, typically as shown in Fig. 12-13.

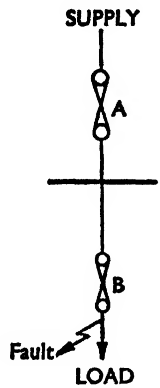


FIG. 12-13.

Here fuse A is called the "major" fuse and B the "minor" fuse, and to attain positive discrimination, the "major" fuse must be unaffected by the passage of fault current which causes the "minor" fuse to operate. To achieve this, a ratio of 2 : 1, or more, in current rating is required between the "minor" and "major" fuse where the fault level is high, but on systems where the prospective currents are low and the fuses do not exhibit "cut-off," the ratio need not be so wide. In many applications the subdivision of loads is such that the 2 : 1 ratio is easily exceeded.

It is important for the maintenance of discrimination that fuse A in Fig. 12-13 must be able to carry the through fault current during the time it is being cleared by fuse B without deterioration. It will of course warm up but on cooling its condition must be as good as new in order that it may at some future date again discriminate with a replacement fuse B. The first principle therefore to be observed is that the *pre-arcing time* of the "major" fuse must be *greater* than the *total operating time* of the "minor" fuse. But it has already been indicated (page 366) that when the pre-arcing time is less than 0·02 seconds, the total operating time is difficult to determine so that reference to characteristic curves for these short times cannot reliably give a clue to discrimination and here it is suggested that the curves of

admitted energy (I^2t) be used to select discriminating fuses. These curves are those in Fig. 12-10 and the method of selection is as follows:—

The system fault level is known to be 15 000 amperes prospective (r.m.s. symmetrical) and reference to Fig. 12-9 shows this to be above the value at which a 200 ampere "minor" fuse (B in Fig. 12-13) exhibits "cut-off." Fig. 12-10 indicates that the *total operating time I^2t* for this fuse is approximately $5 \cdot 10^5$ amp²sec. and extending this value to the right to the curve of *pre-arcing I^2t values*, it is found that the fuse whose pre-arcing value exceeds $5 \cdot 10^5$ is a 400 ampere fuse with a value of $8 \cdot 10^5$ amp²sec., approximately, this then being the discriminating rating for the "major" fuse A. It is noted in passing that a 300 ampere fuse has only $4 \cdot 10^5$ amp²sec. and is therefore non-discriminating.

In the literature of The General Electric Co. Ltd. concerning their fuse-links, a table as in Table 12 : 3 below is given as a guide to the selection of fuses to give correct discrimination.

TABLE 12 : 3

Prospective fault current (amps)	Major fuse rating (amperes)														
	4	**6**	**10**	**15**	**20**	**25**	**30**	**40**	**50**	**60**	**80**	**100**	**125**	**160**	
500	2	4	6	10	15	15	20	30	30	50	60	80	100	125	Minor fuse rating (amps)
1 000	2	4	6	10	10	15	15	25	25	30	50	80	100	125	
4 000	2	4	6	10	10	15	15	20	20	25	30	40	60	80	
10 000	2	4	6	10	10	15	15	20	20	25	30	40	50	60	
16 500	2	4	6	10	10	15	15	20	20	20	30	40	50	60	
33 000	2	4	6	10	10	15	15	20	20	20	25	40	50	60	
46 000	2	4	6	10	10	15	15	20	20	20	25	40	50	60	
80 000	2	4	6	10	10	15	15	20	20	20	25	40	50	60	

Prospective fault current (amps)	Major fuse rating (amperes)													
	200	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**	**800**	
500	160	200	250	300	—	—	—	—	—	—	—	—	—	Minor fuse rating (amps)
1 000	160	200	250	300	350	400	450	500	550	—	—	—	—	
4 000	100	160	250	300	350	400	450	500	550	600	650	700	750	
10 000	100	125	160	200	200	250	300	350	450	500	600	650	750	
16 500	100	125	160	200	200	250	300	300	350	450	550	600	750	
33 000	100	125	160	160	200	250	300	300	350	400	450	500	600	
46 000	100	125	160	160	200	250	300	300	350	400	450	500	600	
80 000	100	125	160	160	200	250	300	300	350	400	450	500	550	

Notes.—This table (General Electric Co. Ltd.) gives the minor fuse which will discriminate with a major fuse of given rating at varying values of prospective current. For example, a sub-circuit where the prospective fault current is 33 000 amperes is to be protected with a 200 ampere fuse. The minimum rating of the major fuse for correct discrimination is found by reading across the table from the prospective current until the value of the minor fuse is found. The rating of the major fuse (here 400 ampere) is in heavy type at the top of the column.

An extension of the example in Fig. 12-13 could be one where three fuses are in series as in Fig. 12-14. Here the principles already noted must

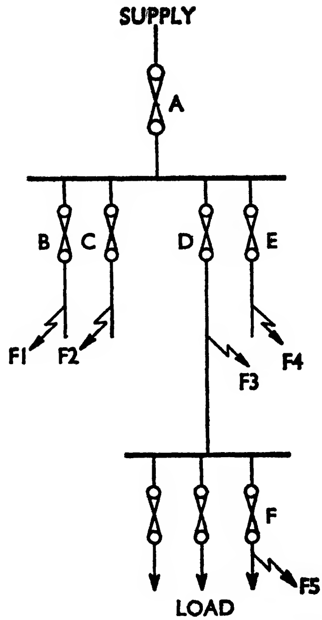


FIG. 12-14.

be applied and for a fault at F1, F2, F3 or F4, fuses B.C.D. or E must discriminate with fuse A, and for a fault at F5, fuse F must discriminate with fuse D.

In his paper, Jacks points out that in certain circumstances it may be necessary to regard discrimination as of secondary importance and quotes a case as shown in Fig. 12-15.

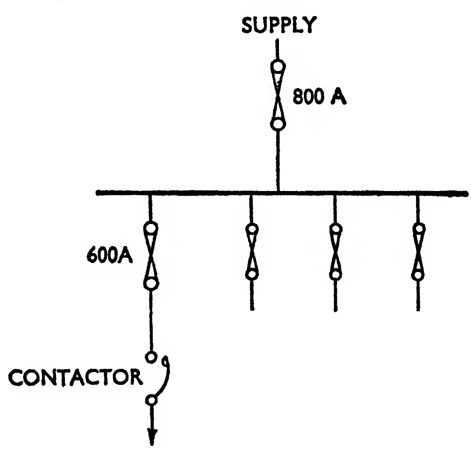


FIG. 12-15.

Here the "minor" fuse rated at 600 amperes is selected to give back-up protection within the through-fault capacity of the associated contactor, whereas the "major" fuse rated 800 amperes, chosen to clear faults in the busbar zone, would not protect the contactor.

Two such fuses would, however, give discrimination at the lower values of prospective current and because both are relatively large, discrimination will occur up to about 15 000-20 000 amperes, the values round about which these fuses start to exhibit cut-off (see Fig. 12-9).

In all that has been said on the subject of co-ordination and discrimination, the assumption has been made that the characteristic time/current curves of fuses and other tripping devices are strictly accurate making no allowance for manufacturing and other variations. To cover these, some tolerance must be allowed and for fuses it is usually plus and minus 5 per cent and for other tripping devices plus and minus 10 per cent (perhaps more on some). Where curves are therefore being compared by superimposition, a band equal to the tolerances should really be added to make sure that with a plus tolerance on one and a minus on the other the desired co-ordination or discrimination is not upset.

It must also be remembered that published characteristic curves for h.r.c. fuses are based on tests which require the fuses and the conductors connected to them to be at ambient temperature approximately. When in service, however, and at the time of operation, load will be being carried and therefore the fuse and conductor temperature will be above ambient and this will have the effect of reducing the pre-arcing and total operating times at certain current values. Guile has studied this in relation to fuses with single wire elements and concludes that at prospective currents above about 15 times the minimum fusing current, the change due to pre-loading in total operating time for the fuse tested is very small and could be neglected. At low over-currents, however, he found the reduction to be such as to be significant when considering close discrimination. An example is quoted of a fuse pre-loaded with its rated current and then subjected to a fault current of twice the minimum fusing current, and it was found that the total operating time was 30 per cent shorter than that when unloaded. This clearly needs consideration under specified circumstances by reference to the fuse manufacturer in the absence of published data.

Another point to consider in the application of fuses is that the temperature rises allowed in B.S. 88 are based on an ambient temperature of 25°C. If fuses are known to be for use where higher ambient temperatures may exist, e.g. in tropical or sub-tropical climates or in others where the room temperature may be high on account of the processes in that room, a reduction in current rating may be necessary, the actual reduction being related to the ambient temperature. For fuses up to about 100/160 amperes, any reduction in rating will not usually occur until the ambient temperature reaches 45/50°C. For fuses above these ratings, reductions may take place earlier in the ambient temperature scale and at an ambient temperature of 40°C a 600 ampere fuse may need to be derated to 400 amperes. Guidance on this can only be obtained by reference to the particular manufacturer in the absence of published data.

Clause 8 of B.S. 88 : 1952 states that every fuse shall be assigned for convenience to one or more of 5 categories of duty distinguished by the

values of prospective current of the test-circuit stated in the table below, and denoted respectively by the numbers 1, 2, 3, 4 and 5, the numbers 1 to 4 being preceded always by the letters AC or DC according respectively to whether the fuse is suitable for use in alternating-current or in direct-current circuits, and the number 5 being preceded always by the letters AC. The category of duty to which any fuse is assigned shall be one having a distinguishing value of prospective current of test-circuit not greater than the breaking-capacity rating of the fuse. The power-factor of an a.c. test-circuit and the time constant of a d.c. test-circuit shall be the same for all tests for a given category of duty, and shall be of appropriate values as stated in the Table 12 : 4.

TABLE 12

Category of duty	Prospective current of test-circuit (amperes)	Power-factor (lagging) of test-circuit not greater than	Time-constant of test-circuit not less than	Equivalent MVA at 440 V a.c.
AC1 and DC1	1 000	0·6	0·003 0	0·75
AC2 and DC2	4 000	0·4	0·004 0	3·0
AC3 and DC3	16 500	0·3	0·010 0	12·5
AC4 and DC4	33 000	0·3	0·015 0	25·0
AC5	46 000	0·15	—	35·0

As a guide to fuse selection for a particular type of load, the following may be regarded as representing average practice but due note must be made of the earlier discussion in this chapter.

Fluctuating loads are those in which peaks of comparatively short duration occur. Examples of this type of load are found in transformer, fluorescent lighting, capacitor and motor circuits. In the first two cases, the fuse selected has to be of such rating that it will withstand the transient current surge on switching-in. Selection will depend to some extent on the fusing factor of the fuse proposed, but it is suggested that the chosen fuse should generally have a normal rating 25 to 50 per cent above the normal full load current of the apparatus to be protected. Similar selection is recommended for capacitor circuits, but here the tendency should always be towards the higher percentage. This type of circuit is particularly difficult because, on switching in, there is a heavy current surge of a highly transient nature and of high natural frequency.

The selection of fuses for motor circuits will depend, of course, on the value of current taken at starting which, in turn, is dependent on the motor design and the method of starting (e.g. direct-on, star/delta, stator/rotor, etc.). In addition, correct selection depends on a knowledge of the length

of time the motor takes to accelerate and for the current to fall to its normal full load value. These are factors which should be obtained from the motor manufacturers whenever possible. Given this information, it is possible to choose a fuse whose characteristic time/current curve lies at all points *above* the curve of motor starting current curve.

This has been illustrated in Fig. 12-12, and it may be noted that it is essential to have an ample gap between the two curves at the point "A" where the curve of motor starting current starts to droop. If this gap is small and the motor is subject to frequent starting—with the possibility of stalling—then the fuse may suffer deterioration leading to subsequent unexplained operation.

When the starting current is not known, useful approximations are (a), that the starting current of a direct-on-line started motor is about 7 or 8 times the full load current and (b) that the starting current of a motor with a 75 per cent auto-transformer starter tapping is about 4 times the full load current and $2\frac{1}{2}$ times with a 60 per cent auto-transformer starter tapping. This latter figure also applies to star/delta starting while for slip ring motors (stator-rotor starters) a fuse selected to meet normal running conditions is adequate.

On the other hand a steady load is one which will fluctuate but little from the normal value (as for example in heating circuits) and in such cases selection will depend on whether the fuse has to give overload *and* short-circuit protection or just short-circuit protection. If the former is required the fuse chosen should have a current rating as near to the normal circuit current as possible. If for short-circuit protection only, then a fuse of higher normal rating may be chosen because at short-circuit values of current, the operating time will be very little more than for a fuse of lower rating and the advantage of a lower running temperature will be gained.

Although not basically different in so far as it is a fuse-link, reference should be made to one design which incorporates a striker pin. In this the striker pin is arranged to function after the fuse element proper has cleared the circuit and in functioning, the pin moves to upset the latching-in mechanism of a circuit-breaker causing the latter to open, or to operate an auxiliary contact in the control circuit of a contactor, or to operate an auxiliary contact to cause an audible or visual alarm to be given.

The striker pin is held after operation so that it can not be ejected completely nor can it be pushed back into the fuse body. The force can be varied to suit the application ranging from several pounds for mechanical tripping to one or two pounds if to operate auxiliary contacts. After operation the striker pin acts additionally as an indicator to show which fuse has operated.

The striker pin assembly is generally as shown in Fig. 12-16 from which it will be seen that an ignition wire passes through a sealed compartment containing a charge of powder. Within the powder the ignition wire is slightly weakened and, after the main fuse elements (of relatively less resistance) have melted to clear the circuit, current is transferred to the ignition wire acting as a high resistance shunt and this, heating up, causes the powder charge to be fired and force the striker pin upwards to the limit of its travel.

In a design of oil-tight cartridge-fuses for voltages in the range 3·3 kV to 33 kV and for use in fuse-switches of the types described in other chapters, EMP Electric have developed a thermal type striker. In addition to function-

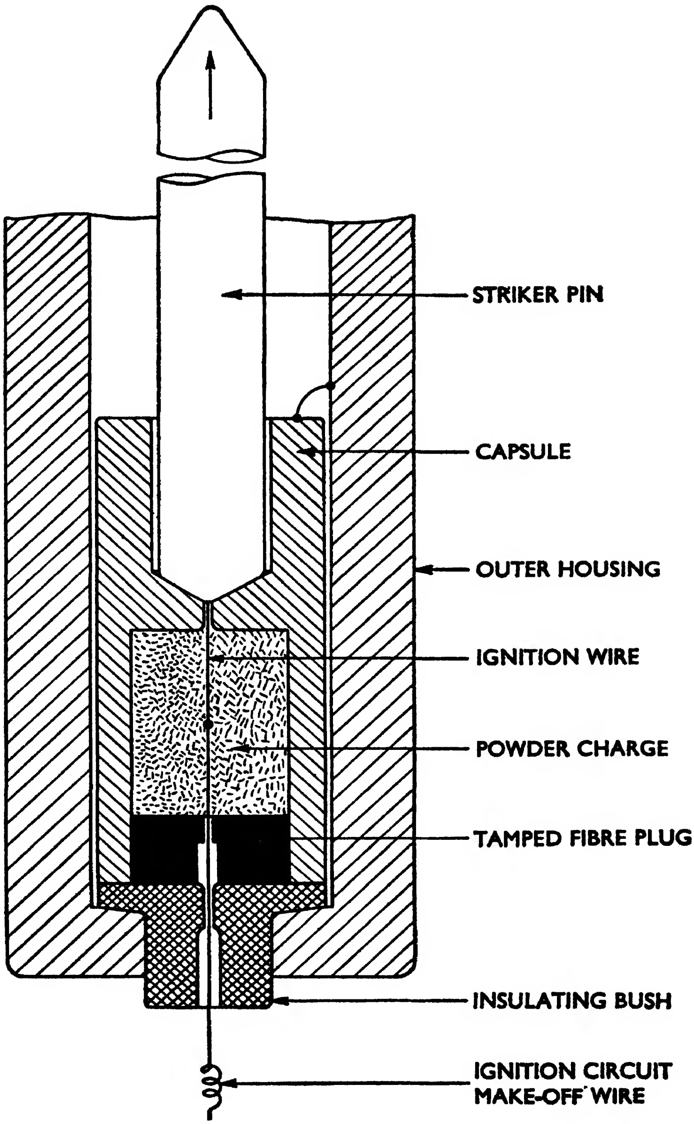


FIG. 12-16.—*Elements of striker assembly greatly enlarged (EMP. Electric, Ltd.).*

ing under fault conditions as previously described, this device functions when overheating of the fusible element occurs for other reasons (as for example if a fuse of incorrect rating has been installed). In these circumstances, there will be an IR drop across the striker circuit sufficiently high to allow current to flow and set off the striker without the fusible element melting.

The application of fuses with a striker pin ensures, when used in association with an automatic circuit-breaker or contactor, that if one fuse only operates, the three phase circuit is disconnected, avoiding, in motor circuits particularly, the hazards of "single phasing". Under these conditions it is known that a running motor will continue to run on the two remaining healthy lines but with an excess of current in those lines and in the motor windings.

It is appropriate here to note briefly that medium voltage h.r.c. fuses have been developed not only for power or lighting circuits but for many other purposes as for example fuses in the secondary circuits of voltage transformers, for house service cut-outs, for the protection of coil circuits (contactor closing coils and the like) and for some special purpose applications such as those for use in aircraft (English Electric) and for the protection of semi-conductor rectifiers (English Electric and EMP Electric).

In Chapter V, details have been given of the short-circuit tests which have to be made to prove the rating assigned to circuit-breakers. It is equally necessary to prove that h.r.c. fuses will behave as predicted under overcurrent and short-circuit conditions.

These tests are, in the case of a.c. fuses, single phase in a circuit having a prospective current not less than the breaking-capacity rating of the fuse (see Table 12 : 4) and not greater than 115 per cent of this rating and at a voltage equal to the voltage rating of the fuse with a plus or minus 5 per cent tolerance. In the test at the appropriate prospective current the circuit must be made at a rising voltage of 50 per cent of the peak value, again with a tolerance of plus or minus 15 per cent. From Table 12 : 4 it will be seen that the power factor of the test circuit is defined, the severity at the lower values having been discussed in other chapters and being equally applicable to fuses.

If the fuse tested as above has a "cut-off" current less than the numerical value of the a.c. prospective current, i.e. less than approximately 70 per cent of the numerical value of the symmetrical peak associated with the prospective current, then further tests have to be made at some smaller prospective current such that the "cut-off" current of this smaller prospective value is not less than the numerical value of the smaller prospective current.

In some types of fuse there is, within the range of duty, a prospective current, usually a moderate overcurrent, at which operation is inherently difficult. Manufacturers usually check for this by carrying out tests at a prospective current not less than the minimum fusing current but not more than 1·4 times this value.

The tests as described will therefore prove the ability of a fuse:—

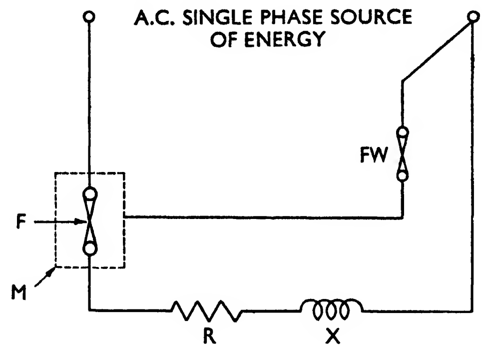
(a) At the upper limit of prospective current for which the fuse is rated, e.g. 46000 amperes in category AC 5.

(b) At values of prospective current where "cut-off" may not occur (see Fig. 12-9) or may occur to such a limited extent that the "cut-

off" current exceeds the numerical value of the reduced prospective current but is less than the associated peak, and

(c) At a very low value of current not much greater than the minimum fusing current.

The test circuit for fuses is that indicated in Fig. 12-17 but B.S. 88 indicates that while testing single fuses in a single phase a.c. circuit means



F FUSE ON TEST
M METAL CASE OR WOVEN WIRE CLOTH (SEE B.S.88/Cl 19)
R RESISTOR IF REQUIRED
X REACTOR IF REQUIRED
FW FINE WIRE FUSE (40 S.W.G. OR SMALLER)
DURING TESTS CASE OR WIRE CLOTH IS CONNECTED TO EARTH THROUGH FW.

FIG. 12-17.—*Test circuit as in B.S. 88:1952, for h.r.c. fuse tests.*

that each fuse shall be tested independently, this does not mean that only one fuse need be tested at once or that the tests need be only on a single phase supply. Details are given showing how three fuses may be tested at once, one in each of three single phase circuits derived from a three phase source.

Typical of tests made at an A.S.T.A. test plant on fuse-links to category AC 5 are those in Figs. 12-18 and 12-19, the former showing the oscillographic record of a test as indicated at (a) above where the prospective current is 46 000 amperes, and "cut-off" occurs at 20 000 amperes, the latter showing the record for a test as at (b) where the prospective current is only 11 000 amperes and the peak "cut-off" current exceeds this, i.e. is 14 250 amperes.

It is of interest here to note the two X-ray photographs reproduced in Figs. 12-20 and 12-21 to show the fused element condition after clearing the rated prospective current (33 000 amperes) and the much lower value of 2 500 amperes.

Having considered the m.v. h.r.c. fuse in some detail it is fitting now to note a few of the many types of switchgear in which it is used. First may be noted the open type of substation fusegear for use in authorised locations

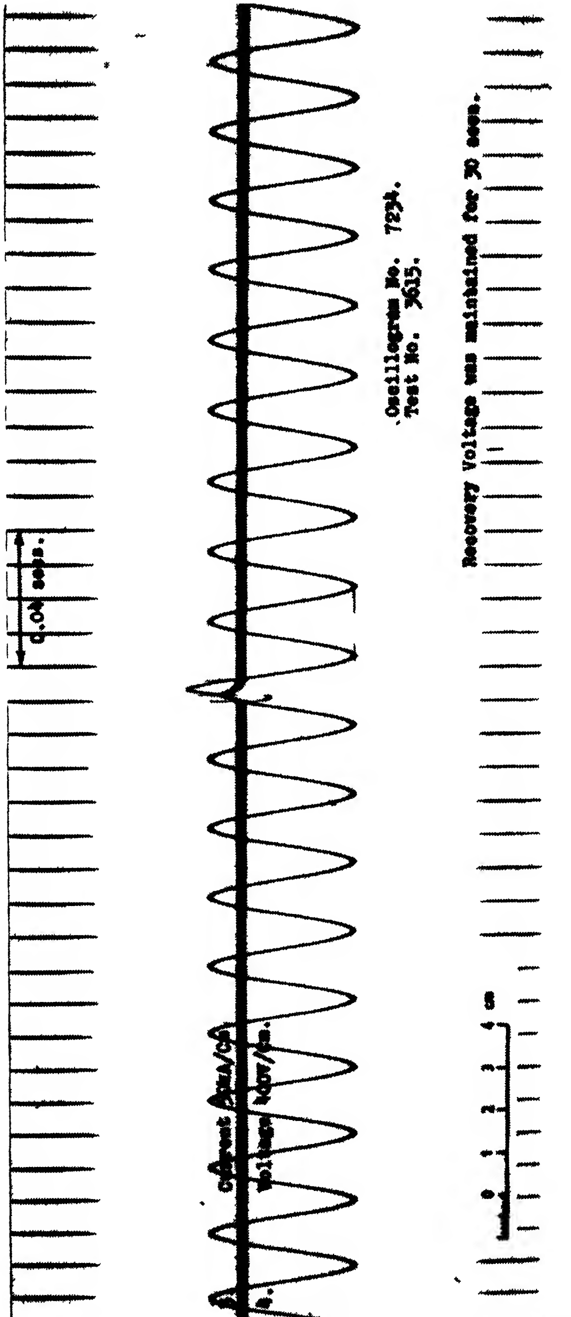


FIG 12-18 —*Short-circuit test oscillogram for "Brilag" fuse link 300 ampere, category,* A C 5 *Prospective current* 46·0 *kA "Cut-off" (peak)* 20·0 *kA Total operating time* 0·0063 *secs (Parmiter, Hope & Sugden Ltd)*

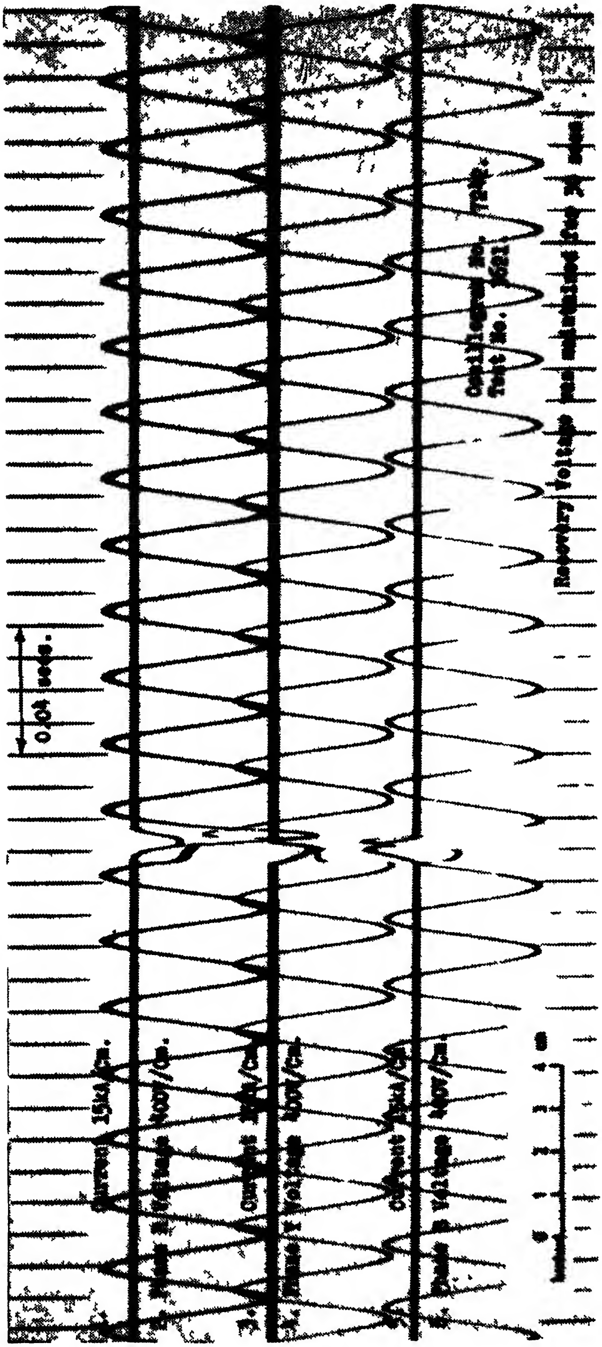


FIG 12-19—*Short-circuit test oscillogram for "Brilag" fuse link 300 ampere, category A C 5 Prospective current 11·0 kA "Cut-off" current (peak) 14 25 kA Total operating time 0 0106 secs (Parmiter, Hope & Sugden Ltd)*

FIG 12-20—*X-ray photograph of fuse after clearing 33 000 amperes (r m s) (A Reyrolle & Co Ltd).*

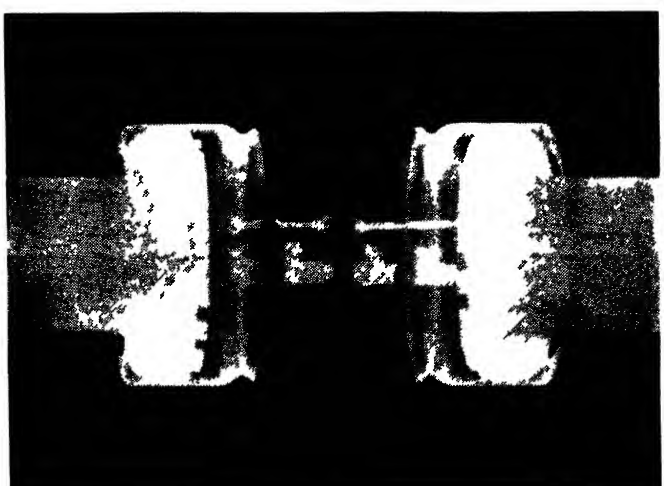


FIG 12-21.—*X-ray photograph of fuse after clearing 2 500 amperes (r.m s) (A Reyrolle & Co Ltd)*

and mainly used for the protection of feeder and distribution cables. This gear can be mounted hard against a wall requiring no back access for making off the cables, and two examples are shown in Figs. 12-22 and 12-23.

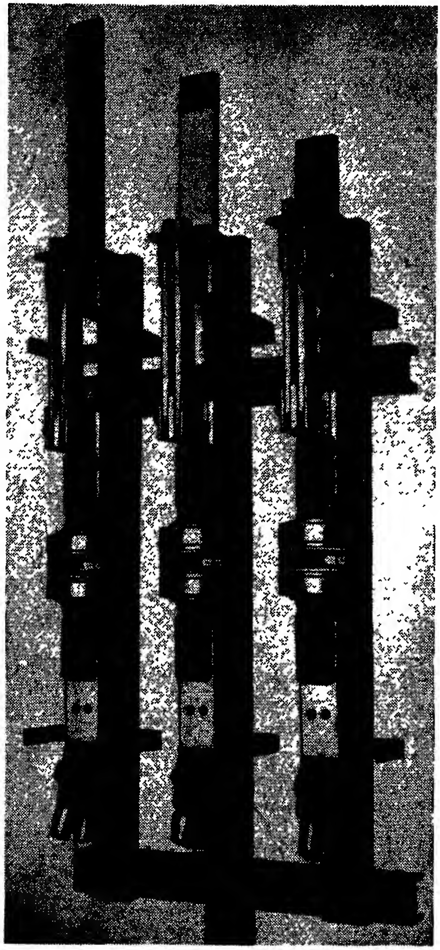


FIG. 12-22.—"*Skeltag" substation fuse gear with single isolation for 3-phase duty (The English Electric Co. Ltd.).*

In Fig. 12-22 it will be noted that the fuse-links are of the bolted type whereas in Fig. 12-23 handle type fuses are employed. Here the fuse carrier is hinged at its lower contact, thus providing its own means of isolation, while in other designs the carrier is held in by thumb-screw driven wedges but designed to permit on-load removal of the carrier.

FIG. 12-23.—*Substation switchboard with circuit-breakers, disconnecting link units and fused distributors. (The English Electric Co. Ltd.).*

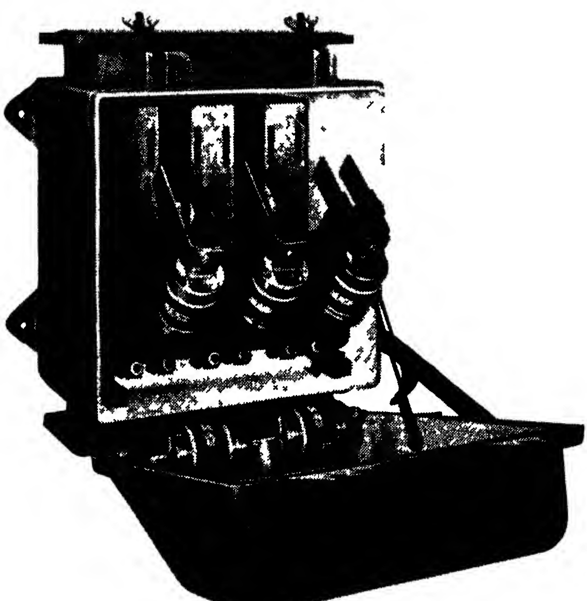


FIG. 12-24.—*"Combination" fuse-switch (The English Electric Co. Ltd.).*

An alternative and well-known form of distribution switchgear is that which comprises a number of fuse-switches, switch-fuses or switches and fuses.

In the first of these the fuse-link is in effect the switch-blade, as for example the unit shown in Fig. 12-24. In this range, units are available with and without shrouded contacts, the former being shown in the illustration, and the design being such that higher overload currents than those specified in B.S. 861 can safely be broken on the switch. These higher currents include the stalled current of a motor and a fault current of medium severity which, during the period when a fuse-switch is closed on to such a medium fault and immediately opened, is not great enough to operate the fuse-link. A typical switchboard of fuse-switches is shown in Fig. 12-25.

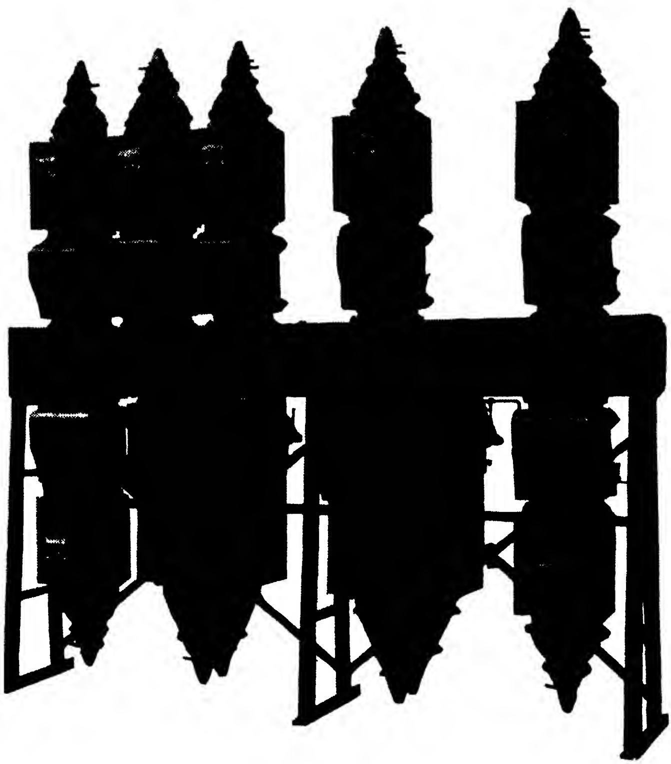


FIG. 12-25.—*Switchboard of "Combination" fuse-switches (The English Electric Co. Ltd.).*

In the other forms, a switch-fuse is an arrangement where both the switch and the fuses are separate components but are nevertheless contained within the same enclosure. Switches and fuses on the other hand are arrangements where separate compartments are provided to accommodate the two components.

An example of the latter is shown in Fig. 12-26, in this case with all circuits arranged below the busbars but available also for above and below mounting. The fuse unit contains handle-type fuses and the cover of this unit is interlocked with the associated switch unit so that the latter must be in the "off" position before access to the fuses can be obtained.

When the load to be switched is inductive or capacitive, a design of

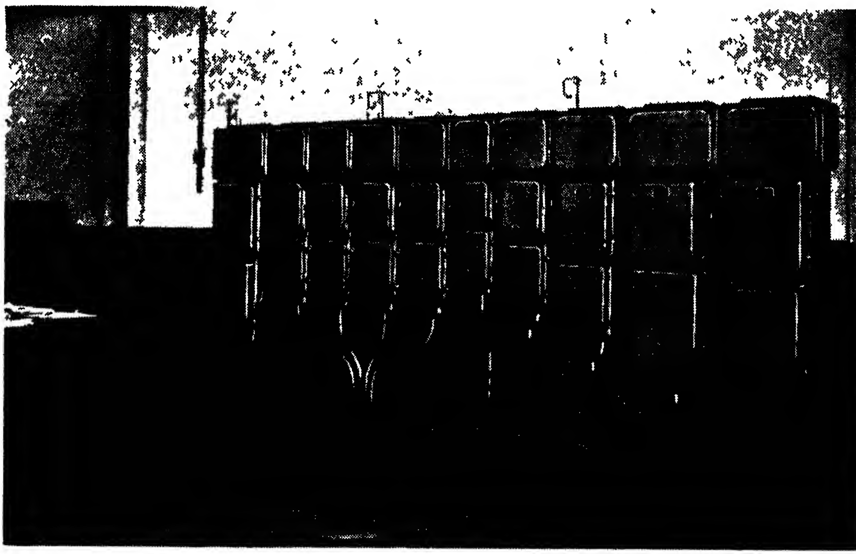


FIG. 12-26.—*Switchboard of "HH" switches and fuses (A. Reyrolle, Co. Ltd.).*

switch is used in which arc chutes are employed as shown in Fig. 12-27, and suitable for switching a.c. welding transformers, power factor correction capacitors or induction motors. Available for normal ratings from 60 to 600 amperes, these switches can make and break currents up to six times the normal current up to the 200 ampere rating and three times on 400 and 600 ampere sizes at power factors as low as 0·3. When associated with h.r.c. fuse-links of equivalent normal current rating, the switches have a making-capacity and through-fault rating corresponding to the maximum duty of the fuses, e.g. Category AC 5 corresponding to 33 MVA at 415 volts, i.e. 46 000 amperes (prospective r.m.s.).

In recent years, very considerable advances have been made in appearance design, a notable example being the English Electric "Superform" switchboard in which a flush-fronted clean outline has been coupled with greater safety for operating personnel. A typical board of this type is shown in Fig. 12-28 which includes not only fuse-switches but also air-break circuit-breakers and distribution fuse-boards without disturbance of the general appearance.

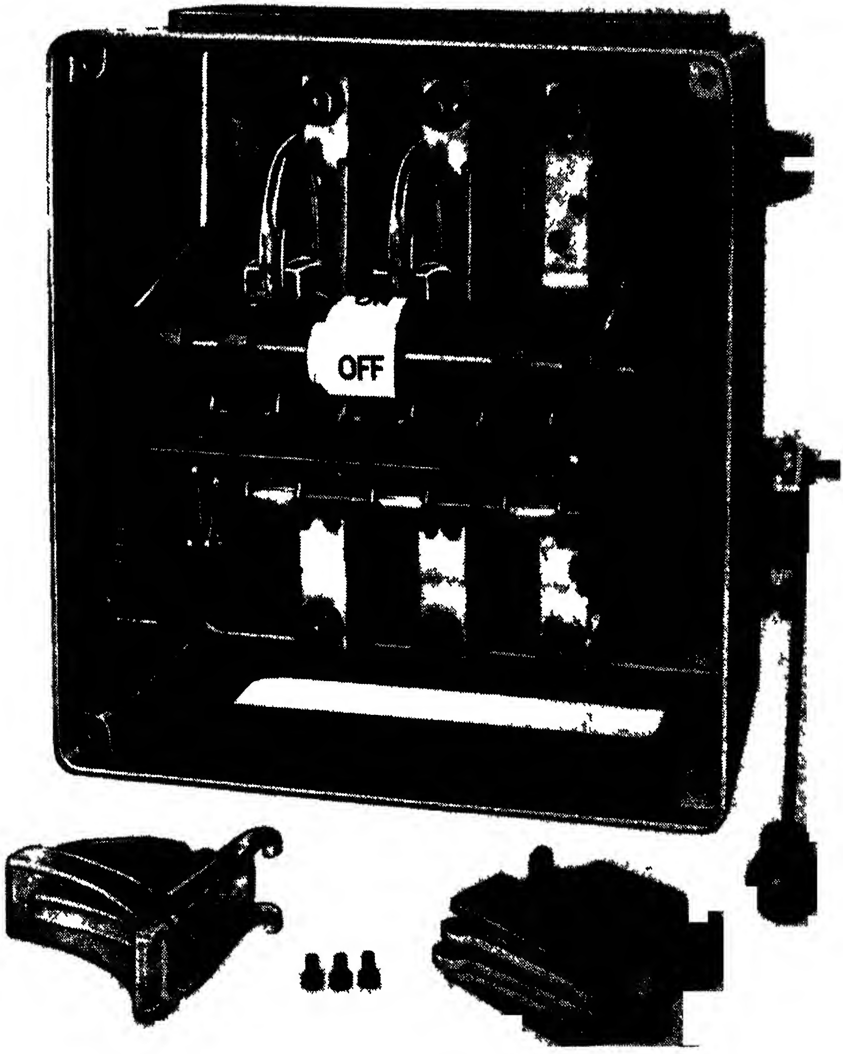


FIG 12-27 —400 *ampere air-break Quick make and break switch for inductive and capacitive load switching One arc chute removed. (A Reyrolle & Co Ltd)*

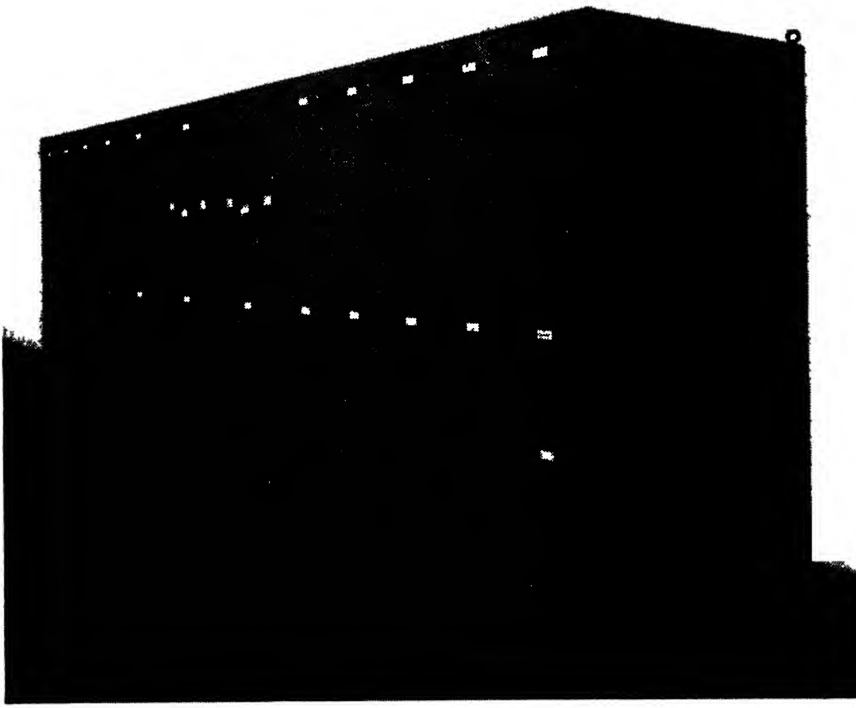


FIG 12-28 —"*Superform*" *switchboard comprising air-break circuit-breakers, fuse-switches and distribution fuse boards*
(*The English Electric Co Ltd*)

In this design, all busbars, connections and risers are fully insulated and the busbars are capable of withstanding through-fault currents up to 35 000 amperes for one or three seconds.

The fuse-switch used is shown typically in Fig. 12-29, the switch being of the double-break type with quick-make and quick-break action. It can stand prospective through-fault currents of 66 000 amperes (r.m.s. symmetrical) equivalent to 50 MVA at 440 volts and can "make" on to fault currents of this magnitude.

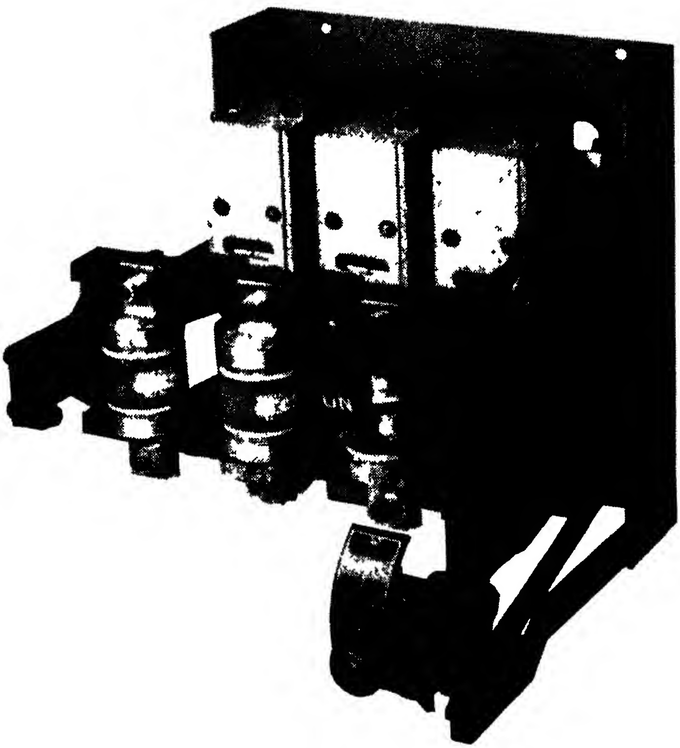


FIG. 12-29.—*"Superform" fuse-switch chassis unit with operating handle in retracted position.*
(The English Electric Co. Ltd.).

Other examples of modern design in switchboards employing fuse-switches are noted in Figs. 12-30 and 12-31, the former including also air-break circuit-breakers in certain circuits, the latter fuse-switches only and designed to line up with group-motor control boards of similar design.

Another design of switchboard in which the switch illustrated earlier in Fig. 12-27 has been incorporated is shown in Fig. 12-32, a board which includes an incoming air-break circuit-breaker of the type described in Chapter IX.

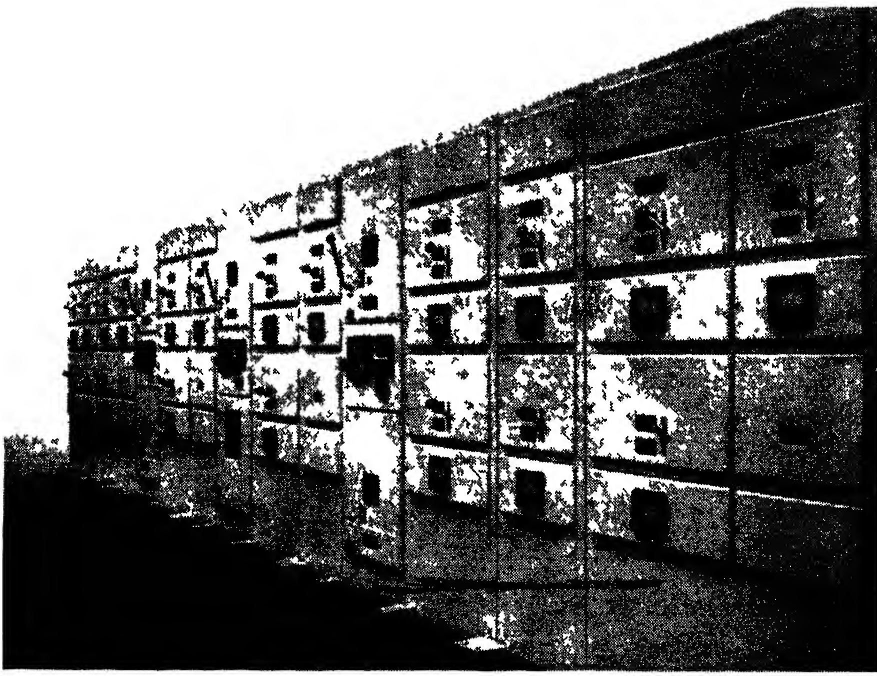


FIG 12-30—*Fuse-switch board with incoming air-break circuit-breakers and fuse-switches (G Ellison Ltd)*

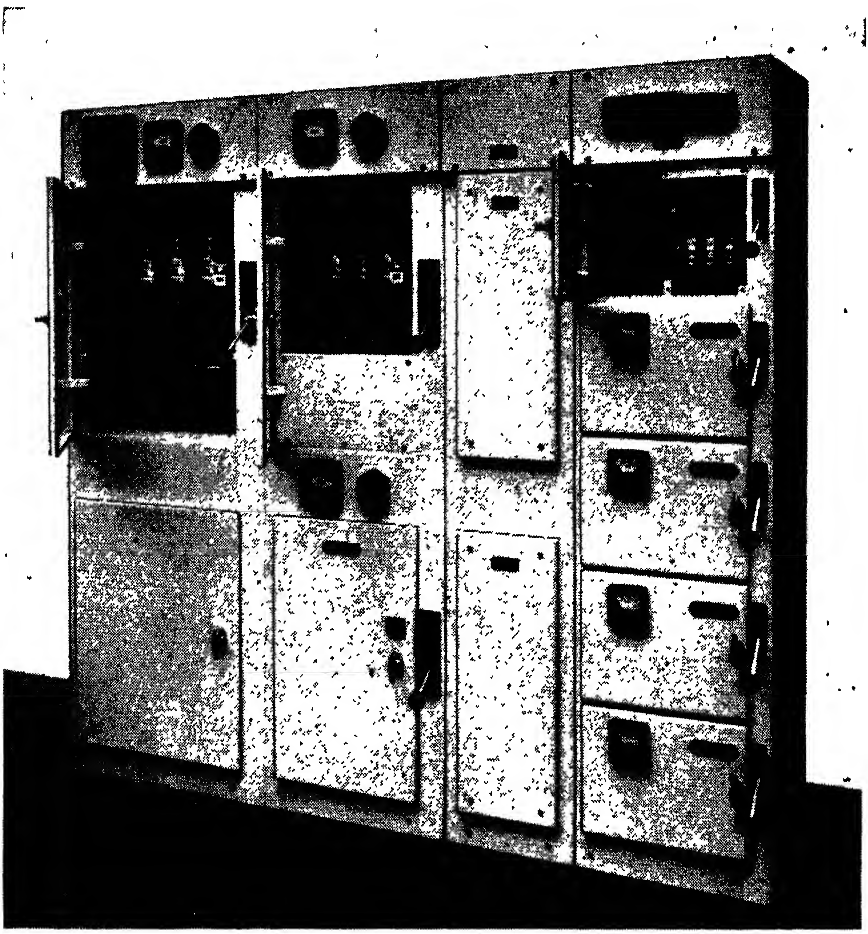


FIG. 12-31.—*Switchboard of fuse-switches showing tiered arrangement (The Belmos Co. Ltd.).*

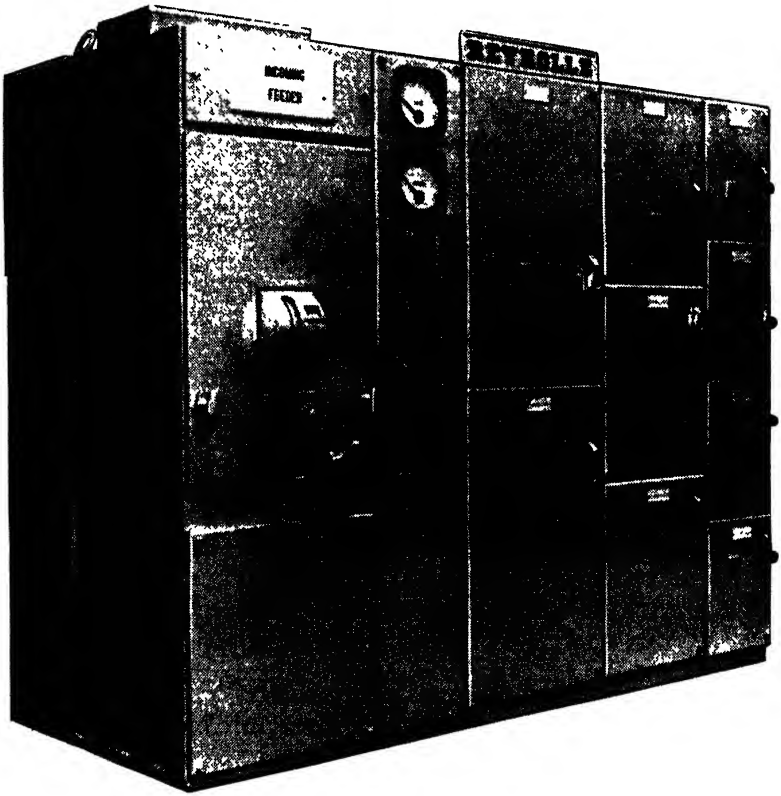


FIG. 12-32.—*Switchboard comprising an incoming circuit-breaker and switch and fuse units in two, three and four tier banks (A. Reyrolle & Co. Ltd.).*

Fig. 12-33 shows in more detail the separate compartments containing the switch and the fuses, the latter being of the handle-type and accessible without exposing the switch or any live contacts.

Reference has been made earlier to the h.r.c. fuse-link which incorporates a striker device for tripping out a three phase circuit-breaker on the occurrence of any one or more fuse operating. Figs. 12-34 and 12-35 show examples of this application, the former to an oil circuit-breaker, the latter to an air-break circuit-breaker.

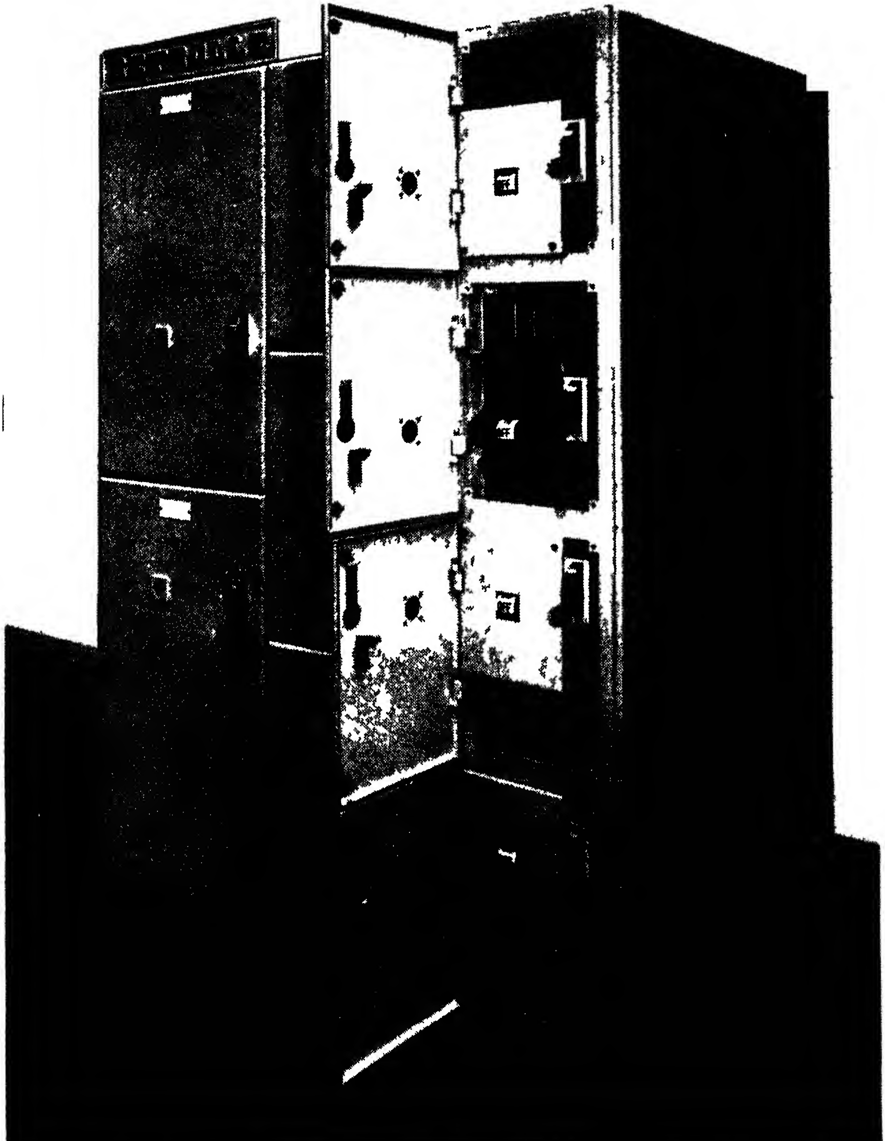


FIG 12-33 —*Showing doors on switch and fuse units open to give access to fuses On one unit the protective shield over the switch contacts has been removed for illustration purposes (A Reyrolle & Co Ltd)*

Both examples are typical of the use of h.r.c. fuse-links being applied to back-up circuit-breakers of moderate capacity, i.e. 15 MVA for the oil breaker and 7·5 MVA for the air-breaker, the fuse-links making both good for an interrupting capacity of that assigned to the fuse-link, e.g. 25 or 35 MVA depending on category. Both breakers are fitted with magnetic direct-acting overload releases and the problem of the cross-over characteristic of the time/current curves as discussed in relation to Figs. 12-11 and 12-12 has to be studied in such applications. In each design the fuse-link

FIG. 12-34.—*Industrial type oil circuit-breaker incorporating back-up striker-pin fuse-links (Johnson & Phillips Ltd.).*

striker pin and the overload trip plunger are arranged to operate to upset the latching-in mechanism of the circuit-breaker and so cause it to open.

A well-known example of back-up protection by h.r.c. fuses is that applied in motor control gear where the contactor is not expected to have a high interrupting capacity in its own right. Here the back-up fuse-links are generally of the non-striker type but examples do exist where the striker pin type has been used, the striker pin in this case functioning to operate a set of auxiliary contacts connected in the control circuit of the contactor.

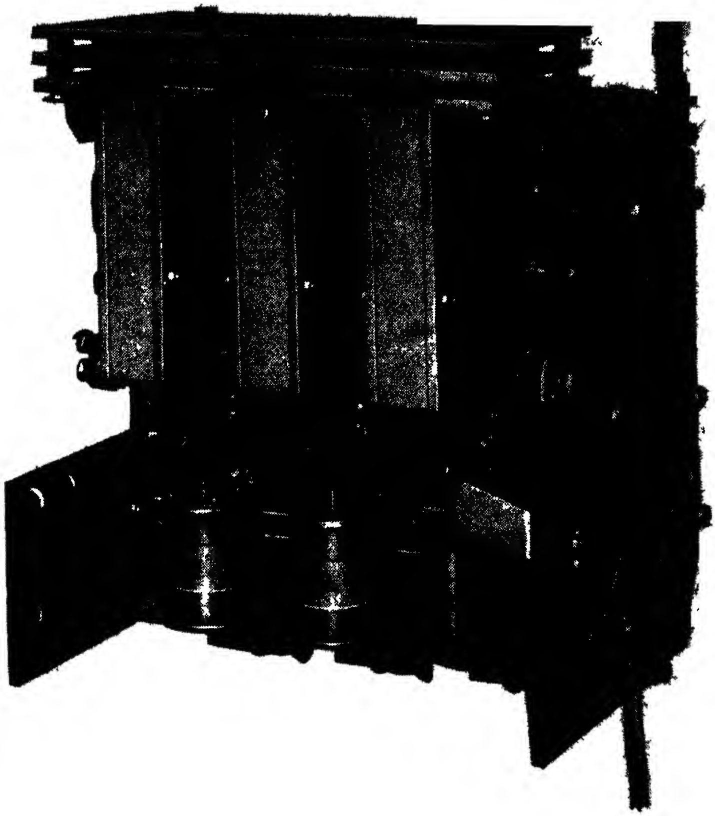


FIG 12-35 —*Circuit-breaker with back-up striker-pin type fuse-links (The Belmos Co Ltd)*

AUTHOR'S NOTE

In previous editions, one or two illustrations were included to show the characteristic time/current curves of particular h r c fuse-links Because of the number of makes available it has been thought wise to omit such curves on this occasion, leaving the reader free to compare the various and numerous curves himself from manufacturers' published data

BIBLIOGRAPHY

B.S. 88 "Electric Fuses".

Electric Fuses, Dipl-Ing H. Läpple (Butterworths Scientific Publications).

Electric Fuses, H. W. Baxter (Edward Arnold & Co.).

"The Fuse—1896/1941," W. E. Bradshaw, "Electrical Times," 1941, p. 406, No. 99.

"The High-Rupturing Capacity Cartridge Fuse with Special Reference to Short-Circuit Performance," J. W. Gibson, "Journal I.E.E.," 1941, No. 88, Part II, p. 2.

"Fuses v. Circuit-Breakers," G. Cluley, "Electrical Review," 1943, No. 132, p. 143.

"Excess Current Protection by H.R.C. Fuses on Medium-Voltage Circuits," R. T. Lythall, "Journal I.E.E.," 1945, No. 29, Part II, Vol. 92, p. 419.

"Excess Current Protection by Overcurrent Relays on Medium-Voltage Circuits," A. G. Shreeve and P. J. Shipton, "Journal I.E.E.," 1945, No. 29, Part II, Vol. 92, p. 430.

"Force-Trip Devices: A Field for the High Rupturing Capacity Fuse," R. T. Lythall, "Electrical Review," 1941, No. 128, p. 545.

"High Power Fusible Cut-Outs," L. C. Grant, "Journal I.E.E.," 1926, Vol. 64, pp. 920-941 and discussion pp. 941-959.

"Discrimination Between H.R.C. Fuses," E. Jacks, "Proceedings I.E.E.," Vol. 106, Part A, No. 28, Aug. 1959.

"The Effects of Pre-Loading on Fuse Performance," A. E. Guile, "Proceedings I.E.E.," Part A, Vol. 102, No. 1, Feb. 1955.

"Recent Developments in Medium-Voltage H.B.C. Fuse-Links," R. H. Dean, "Proceedings I.E.E.," Part A, Vol. 105, No. 21, June 1958.

"Correlation of Characteristics," W. J. Elliott, "Electrical Times," 6th March, 1958.

"Parameters for Fuse Performance," H. W. Baxter, "Electrical Times," 28th May, 1959.

"Group Motor Control Boards," R. T. Lythall, "Electrical Review," 30th June, 1961.

"High-Breaking Capacity Cartridge Fuses," A. L. Lawrence, "AEI Engineering," July/August, 1961.

"The Role of the H.R.C. Fuse in the Protection of Low and Medium Voltage Systems," E. Jacks "The English Electric Journal," Vol. 17, No. 3, September, 1961.

"Protection of Electrical Apparatus—Part II H.R.C. Fuses," J. Feenan, "Electrical Journal," July, 1961.

CHAPTER XIII

BUSBAR SYSTEMS

CHAPTER XIII

BUSBAR SYSTEMS

The busbar system selected for any particular application will depend largely on

(a) The degree of flexibility of operation required.
(b) The degree of immunity from total shut-down desired.
(c) The relative importance of the location.
(d) First cost, where economics are a primary consideration.

In a major plant, e.g. generating station or primary distribution centre, an elaboration of the busbar system is nearly always justified. Here, a shut-down results in the disconnection of consumers over a wide area, and a system which enables reconnection in the shortest possible time is essential. In the small substation the number of connected consumers may be small and the dislocation due to a shut-down is thereby reduced. First cost is also a primary consideration in small substations and therefore the elaborations of a major station are not warranted.

In the following pages will be found the main basic layouts. There are various ways in which two or more of these can be combined and such combinations find useful application in certain circumstances.

SINGLE BUSBAR.

The simplest of all busbar connections is that where a single set of busbars extend the length of the switchboard without break, and to which

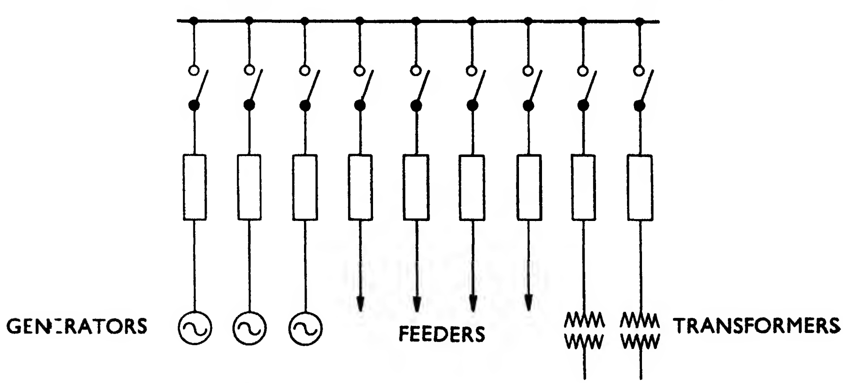


FIG. 13-1.—*Single busbar system.*

all generator, feeder and transformer circuits are connected. This method is general for d.c. switchboards, and is one usually chosen for the smaller a.c. substation or generating station.

The single busbar scheme is shown in Fig. 13-1. It is to be noted that if at any time a busbar fault occurs, all feeders will be deprived of supply. Busbar cleaning and maintenance will involve a complete shut-down. In compound-filled types of switchgear, busbar faults and the need for cleaning should not arise, so that for this type, single busbars are often suitable. A further point not to be overlooked is that under fault conditions the combined plant of the station feeds into the fault and this may place some limitation on the size of station which can use continuous busbars, i.e., without sectionalising. In Fig. 13-1 means of isolating the circuit-breaker are indicated only on the busbar side. If, on feeders or transformers, there exists any possibility of a feed back, double isolation must be used. This point should be particularly watched in transformer circuits where they may be paralleled on the m.v. side for distribution—such paralleling may arise through an indirect route and not necessarily at a common point such as the m.v. switchboard.

SECTIONALISED SINGLE BUSBAR.

The simple act of sectionalising the busbar results in many advantages. Chief among these is the facility it provides in operating the system in that one (or more) sections can be completely shut down for maintenance or repair without interfering with supply from other sections. The number of sections will largely depend on the importance of the station or on the

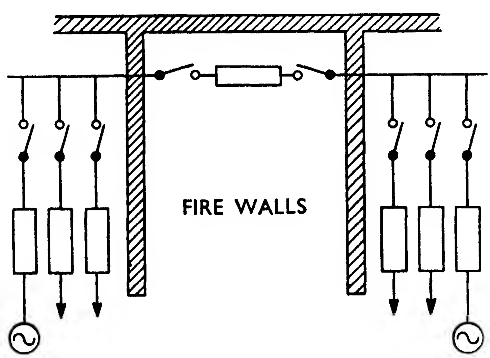


FIG 13-2.—*Sectionalised single busbar system.*

limitation of short-circuit value desired (see Chapter III). It is an important advantage of sectionalising that circuit-breakers of lower breaking capacity may be used by running normally with sections electrically segregated. If feeders to any one point are duplicated, it is usual to connect these to different sections. If sectionalising has been adopted in order to obtain a reduction in fault value, care must be taken not to parallel feeders off different sections of the main switchboard at the remote point, i.e., sectionalising may be necessary at the remote point also. In general, the sectionalising switch should be a circuit-breaker so that the sections may be uncoupled even if a load transfer happens to be being made. An air-break isolator, so often used for sectionalising, is not suitable for this

purpose, and if used, should be suitably interlocked so that it can only be opened or closed under no-load conditions. Air-break isolators should preferably be confined to m.v. systems.

Where a circuit-breaker is used, it should have double isolation, in order that the circuit-breaker may be completely isolated from adjacent sections. A simple sectionalised single busbar scheme is shown in Fig. 13-2 which also indicates how fire risks may be reduced by housing the sectionalising circuit-breaker within fireproof walls. It will be appreciated that the sections must be synchronised before the section switch is closed.

RING BUSBARS.

From the sectionalised scheme, the next step to give greater flexibility is to join the ends of a multi-sectionalised busbar, to form a ring, as shown in Fig. 13-3. By this means, generating plant on any section can be utilised to supply the feeders on any adjacent section.

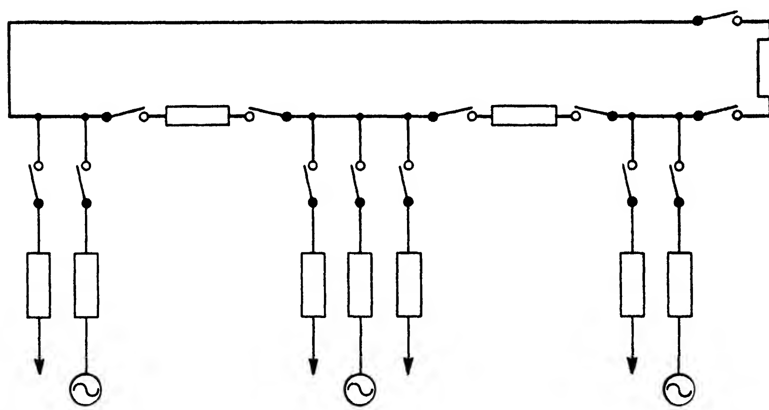


FIG. 13-3.—*Sectionalised ring busbar system.*

DUPLICATE BUSBARS

In the more important stations, the use of duplicate busbars is almost universal. The advantages of the scheme from an operating and maintenance point of view more than outweigh the additional cost. Usually, one set of bars are designated "main" and the other "reserve" or "hospital." This infers that normally the "main" bars are in use with the other set available in the event of trouble. Apart from cleaning and maintenance, the existence of a second set of bars is of considerable value when, for some reason, a particular circuit demands special treatment, such as testing out a new feeder,

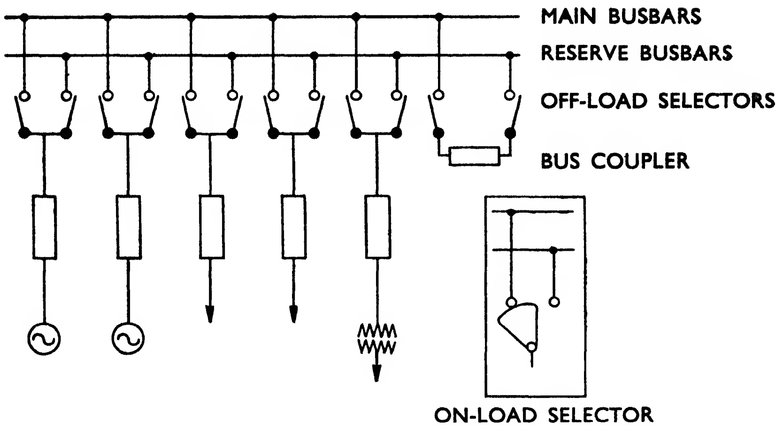


FIG. 13-4.—*Duplicate busbar system.*

or the running of an existing feeder at a higher voltage than normal to compensate for an abnormal voltage drop. Similarly, it is possible to carry out commissioning tests on new plant on the reserve busbars without interfering with normal services on the main bars.

Duplicate busbars involve the use of selector switches at the switchgear. In cubicle gear, these take the form of ordinary isolating switches. In metalclad gear, removable plugs are sometimes supplied, these being moved by hand to one position or another. Alternatively, oil-immersed selectors are used—one type being an "off-load" arrangement where a single blade, hinged at one end, is moved by means of an external handle to one or other set of contacts connected to the main or reserve busbars. In another form, the blade is in the shape of a fan and makes contact with one set of contacts before breaking on the other, and is an "on-load" type. These are described and illustrated in more detail later.

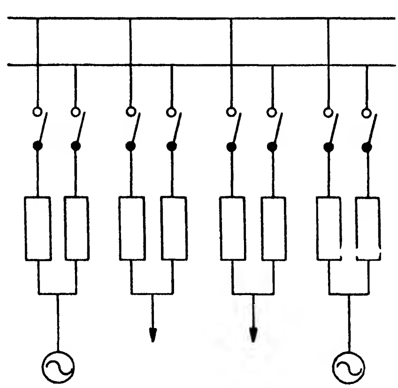


FIG. 13-5.

The two sets of busbars must be paralleled before operating the selector switches, and this is done through a busbar coupler switch, as shown in Fig. 13-4.

This switch may or may not have automatic features, but in any case should be interlocked with the selector switches. This is usually accomplished by means of keys, suitably trapped until the busbar coupler is closed. This interlock can be combined with a synchronising scheme.

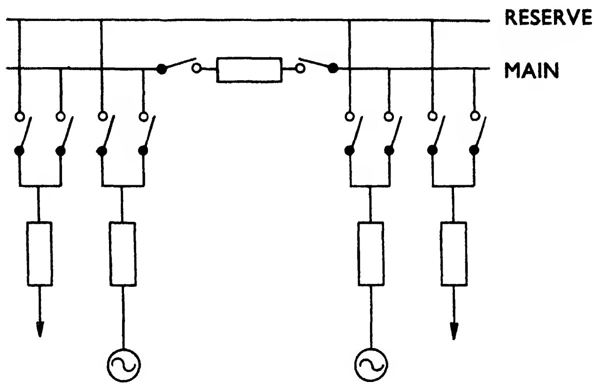


FIG. 13-6.

In an alternative form of duplicate busbar scheme, duplicate circuit-breakers are used for each circuit. This scheme does not require a busbar coupler switch, but it is costly and is generally only used in major stations. It is a scheme which gives greatest facility for circuit-breaker maintenance. The layout is shown in Fig. 13-5.

SECTIONALISED DUPLICATE BUSBARS.

This scheme is shown in Fig. 13-6 and provides considerable flexibility. Any section of busbar can be isolated for maintenance while any section can be paralleled with any other through the reserve busbars. Normally, sectionalising of the reserve bars is unnecessary, although this can be done if required. Busbar coupler switches can be provided on each section.

DUPLICATE BUSBARS WITH BY-PASS ISOLATORS.

Instead of using duplicate circuit-breakers, a scheme may be used in which a by-pass isolator is incorporated as shown in Fig. 13-7. It is only

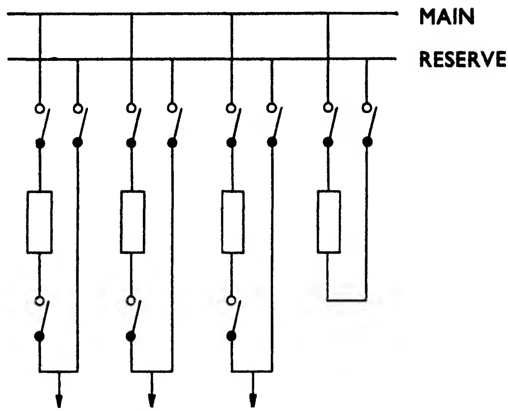


FIG. 13-7.

suitable for cubicle type switchgear and the by-pass isolating switch is generally connected to the reserve busbars. If it is required to take a circuit-breaker out of service, the circuit may be kept in service by closing the by-pass isolator after the circuit has first been cleared both at the

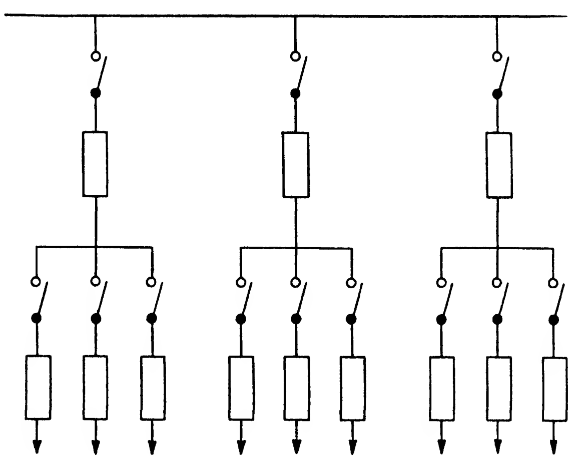


FIG. 13-8.

breaker and its isolating switches, and then closing the busbar coupler. As the circuit still demands protection, this is usually provided at the busbar coupler, by means of back-up overcurrent protection.

GROUP SWITCHING.

It often happens that when the station capacity increases, existing switchgear will have insufficient breaking capacity. If there are a considerable number of feeder circuits, it becomes a costly item to replace the circuit-

breakers by new, and a group switching scheme is often resorted to. This scheme is shown in Fig. 13-8, where groups of feeders are connected to the generators through circuit-breakers of ample breaking capacity. It will be clear that if a fault occurs on any of the feeders, the group circuit-breaker must open to clear it. This is a disadvantage in that all feeders connected to that group circuit-breaker are out of service until the faulty circuit is cleared. In order to ensure the opening of the group circuit-breaker, a scheme of interlocking is necessary, usually accomplished through relays. This scheme will permit a feeder circuit-breaker to clear an overload within the capacity of that circuit-breaker.

Before adopting the group switching scheme, it is essential to check that the feeder circuit-breakers can carry the maximum fault current until cleared on the group circuit-breaker. It must also be remembered that a feeder circuit-breaker may be closed on to a fault, a duty for which it may not be suitable.

A modification of the scheme, and one to be recommended, includes reactors between the group feeder and the secondary busbars, as shown in Fig. 13-9.

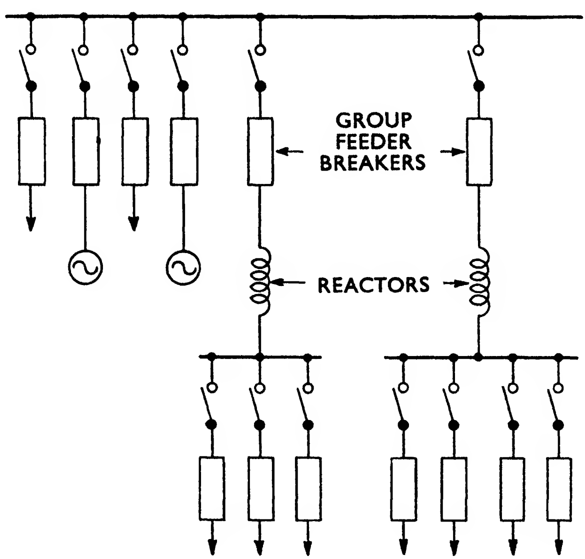


FIG. 13-9.—*Group switching system.*

TRANSFORMER SWITCHING.

In networks where transformers are employed to step up to a suitable transmission voltage, a variety of switching schemes are available. Two of these are shown in Figs. 13-10 and 13-11.

The scheme which allows for switching the transformer and line as a unit is adopted to economise in switchgear, as none is required on the

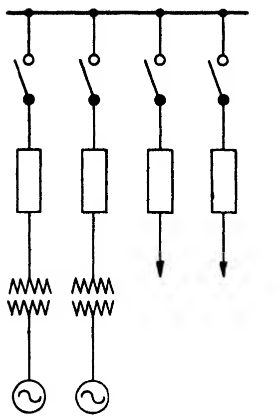


FIG. 13-10.—*Generator and transformer switched as a unit.*

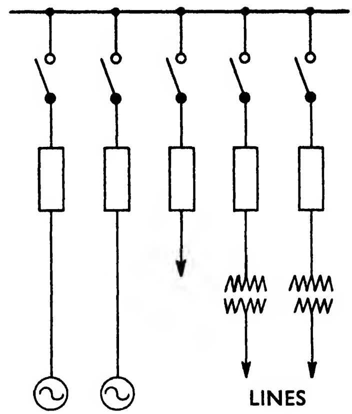


FIG. 13-11.—*Transformer and line switched as a unit.*

h.v. side. It has the obvious disadvantage that a transformer breakdown involves also the loss of the line. The practice of treating a generator and transformer as a unit has the same disadvantage as trouble with one involves the other. It has the advantage that heavy current switchgear at relatively low voltage is not required. The two can be adequately protected as a unit, and magnetising current rush on switching-in is eliminated.

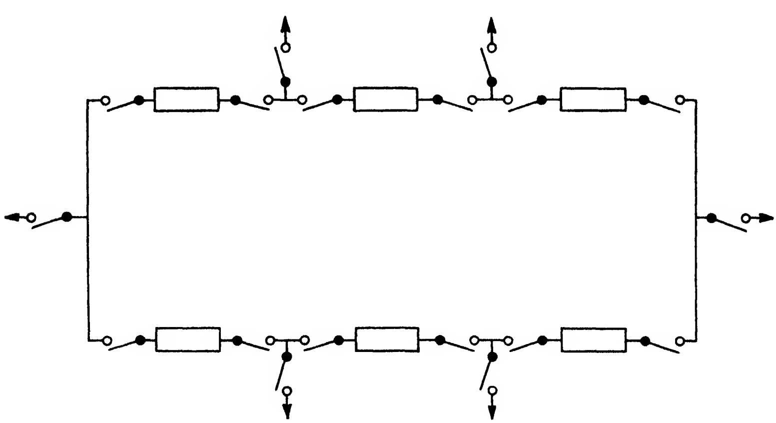


FIG. 13-12.

All the schemes for transformer switching, though shown for single busbars, can be elaborated by the use of duplicate busbars and sectionalising.

MESH SCHEME.

A scheme which has been adopted in major stations is known as the mesh scheme, shown in Fig. 13-12. It is a development of the three-switch scheme adopted on the British Grid network, for schemes where there are more than two feeders. It economises in the use of circuit-breakers (by comparison with a duplicate busbar scheme) but the total number of circuit-breakers is the same as the number of circuits. The saving is in the elimination of the busbar coupler. To make any circuit dead, two circuit-breakers must be opened, i.e., the two adjacent to the circuit in question. Protection must include for the tripping of two circuit-breakers and therefore complicates the scheme.

REACTOR SCHEMES.

Many of the schemes so far considered can have generator, feeder or busbar reactors included in order to reduce the value of fault current to a safe figure. Details of the use of reactors are given in Chapter III, while typical diagrams are given in Figs. 13-13 to 13-16.

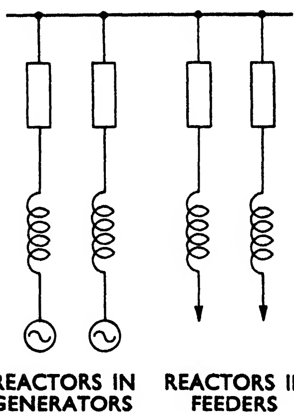


Fig. 13-13.—*Reactors in generator and feeder circuits.*

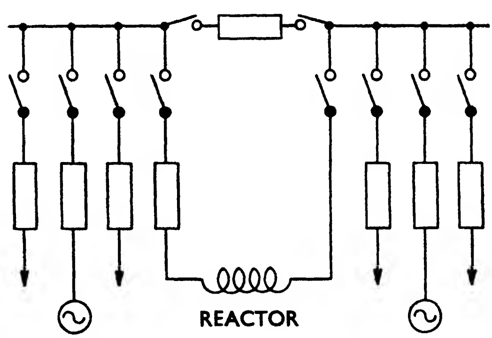


Fig. 13-14.—*Reactor in busbars with short-circuiting switch.*

The busbar systems so far described relate mainly to those employed on high-voltage networks. While it is rarely necessary to adopt duplicate busbars or the more complicated mesh or ring schemes for low-voltage (400-600 volts) switchboards, it is nevertheless true that sectionalised busbars are of considerable importance, particularly in relation to the need to reduce fault values, as demonstrated in Chapter III. In addition, sectionalising effectively reduces the transformer ratings to bring down the normal load currents to be carried by both cables and switchgear, which in itself is a desirable feature.

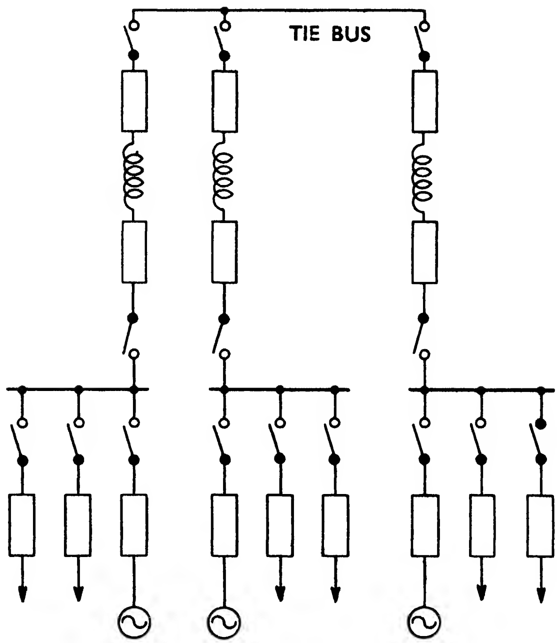
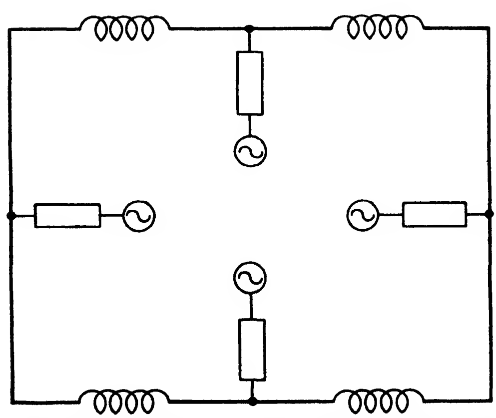


FIG. 13-15.—*Reactors in tie bars.*



MEANS OF ISOLATING OR SHORT-CIRCUITING REACTORS OMITTED FOR SIMPLICITY

FIG. 13-16.—*Reactors in ring busbars.*

The use of two or more small transformer units instead of one large unit has the further advantage that if one smaller transformer is lost due to breakdown or other cause there is no *total* loss of supply as would be the case if the one and only large transformer failed. It is possible in a scheme such as that shown in Fig. 13-17 to assume three 650 kVA units taking the place of one 1 500 kVA unit and the load factor being such that normally only two transformers would be in service leaving the third as a standby.

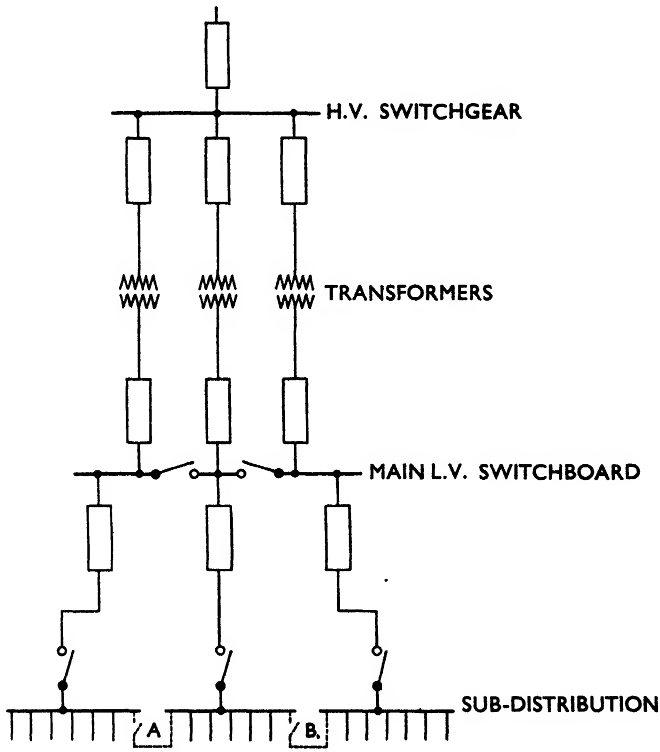


FIG. 13-17.

Sectionalising to obtain a reduction in fault values can only be effective if the transformer and sectionalising switches are adequately interlocked. Under no circumstances must it be possible to have all switches closed at the same time; in fact in the scheme in Fig. 13-17 out of the five switches it

must be possible to have only three or less closed at any one time, while in a scheme with two transformers and one section switch, only two out of three must be closed. Such interlocking is usually achieved by the use of figure locks and keys.

In some circumstances it may be an advantage to have facilities to join the busbars at the sub-distribution point, as shown by the dotted lines at A and B in Fig. 13-17. The advantage of this is that it makes it possible to have one of the feeder circuit-breakers at the main switchboard out of service for maintenance purposes. This, however, means that further interlocking will be necessary to ensure that only three of the five switches (three incoming and two section) can be closed at any one time.

METHODS OF BUSBAR SELECTION.

Where duplicate busbars are employed, some means must be provided whereby the circuit is connected to one set of bars or the other. In open or cubicle types of gear, this simply means the supply of two sets of isolating switches as indicated in the diagrams, Figs. 13-4, etc., but in the various forms of draw-out or drop-down types, whether air-insulated or compound-filled, other methods are necessary and one of the earliest designs was that of plug changing. In this, a set of three plugs is provided which can, with the circuit-breaker isolated, be screwed into the upper or lower set of fixed spouts. This method is shown diagrammatically in Fig. 13-18 where the plugs are indicated as being in the upper orifices thus connecting the circuit-breaker to the upper set of busbars.

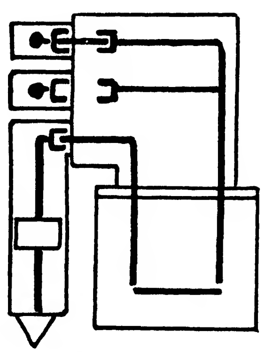


FIG. 13-18.

It is essentially an "off-load" method of selection, involving perhaps, scaling the unit to get at the plugs, and then handling them from one orifice to another. For the smaller current ratings this may not be a serious

handicap, but at the larger current ratings the plugs tend to be rather heavy. It is a form of selection which is applied particularly in types with horizontal isolation and much ingenuity has been shown in devising interlocks to ensure that before a circuit-breaker is put back into service, *all three* plugs have been put into *one* row.

In an effort to provide an easier change-over, the oil-immersed selector switch has been developed. In a chamber carried above the oil circuit-breaker, a three pole changeover switch is accommodated, the three poles being coupled and connected to an external operating mechanism. Two types of this design are used, one an "off-load" type as shown diagrammatically in Fig. 13-19, where the change-over blades are of the "break-before-make" type, and an "on-load" type as shown in Fig. 13-20, where the blades are of the "make-before-break" type. With "on-load" selection by this method, it is usual to provide an interlock with a busbar coupling switch so that the latter must be closed before change-over takes place at individual circuits. Where it is likely that certain generating plant may be connected some to one set of bars and some to the other, synchronising across the busbar coupler is necessary.

The disadvantages of the oil-immersed isolator are that it adds to the quantity of oil per unit, and involves a common connection to both sets of busbars within the selector chamber.

An alternative form of "off-load" selection is that described as a transfer circuit-breaker. In this scheme the circuit-breaker is first isolated completely from one set of bars, bodily moved, and then re-connected to the second set of bars. In vertical isolation types, this involves lowering the breaker carriage, moving it either forward or backward, and then raising it to the desired set of busbars. Diagrammatically this is shown in Fig. 13-21.

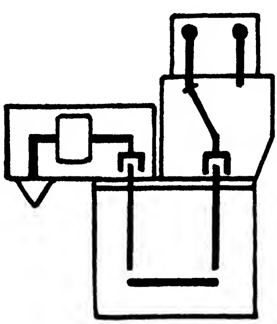


FIG. 13-19.

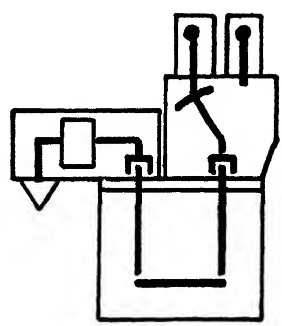


FIG. 13-20.

In the horizontal isolation type it is usual to fix two rows of fixed structures back to back, the circuit-breakers being in use on one row or the other, typically as shown in Fig. 13-22. To move the circuit-breaker involves the use of a transporter truck or a crane and the need for two rows of fixed structures involves considerable floor space.

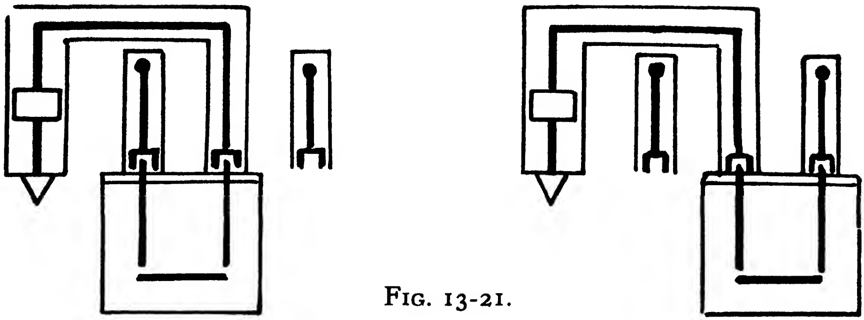


FIG. 13-21.

A variation of the transfer breaker method is sometimes used where two separate circuit-breakers are used per circuit, with suitable interlocks between the pair to ensure that only one is closed at a time. It is a costly method and is only justified on the most important plants and at the higher breaking capacities. This method of selection is shown in Figs. 13-23 (horizontal isolation) and 13-24 (vertical isolation).

Two other methods of busbar selection have been developed, the first comprising a specially designed circuit-breaker having two sets of fixed and moving contacts within a common tank and with a common centre point, generally as shown in Fig. 13-25. The other is a design which permits one set of circuit-breaker stems to be rotated through 180 degrees to make contact with one or other set of busbars, as shown in Fig. 13-26. This is, naturally, an "off-load" form of selection.

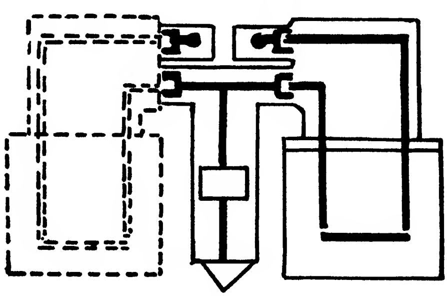


FIG. 13-22.

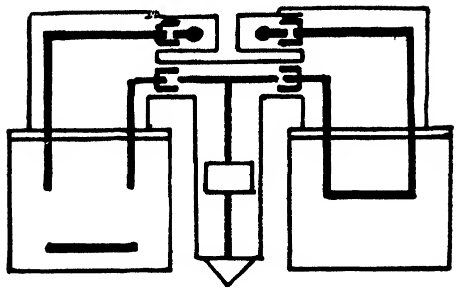


FIG. 13-23.

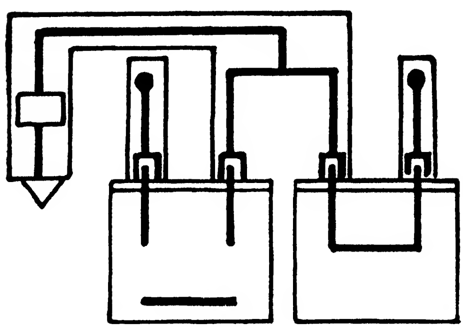


FIG. 13-24.

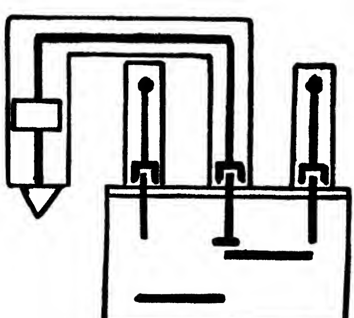


FIG. 13-25.

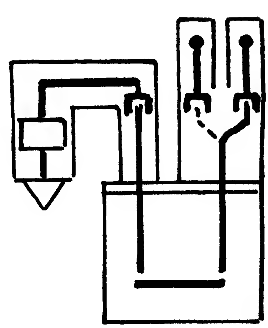


FIG. 13-26.

CHAPTER XIV

BUSBARS AND BUSBAR CONNECTIONS

CHAPTER XIV

BUSBARS AND BUSBAR CONNECTIONS

Two materials offer themselves as commercially suitable for use as busbars and busbar connections in switchgear design, namely copper and aluminium. The relative properties of these are given in the table below.

	Copper	Aluminium
Weight per unit length for equal conductivity	1·0	0·50
Conductivity for equal areas:—		
Electrical..	1·0	0·61
Thermal	1·0	0·56
Tensile Strength (Hard drawn)	1·0	0·40
Hardness (Hard drawn)	1·0	0·44
Modulus of Elasticity	1·0	0·55
Co-efficient of Thermal Expansion ..	1·0	1·39
Melting Point	1·0	0·61

This table shows that for equal conductivity, aluminium is lighter than copper and while this is an advantage in some applications, it is not usually important in many of the indoor types of switchgear up to 33kV. Here, weight is not a deciding factor; rather it is bulk that counts, particularly in metalclad and other enclosed types, and as aluminium conductors must have about 60 per cent greater sectional area than copper conductors for the same current rating, the latter material is often preferred. In other circumstances, where space is of less consequence, aluminium finds many uses, especially for example in open busbar runs such as occur in furnace installations, electroplating plants, large battery rooms as at telephone exchanges, and vertical risers in multi-storey buildings. Aluminium is not subject to "progressive oxidation" in that the oxide film is continuous, very hard and adherent and is stable, thus sealing the metal from further oxidation. This is important when an installation has to operate in high temperatures, or in polluted atmospheres.

Busbars and busbar connections for current ratings of 200 amperes and above, as components of electrical switchgear, are covered by B.S.159, the

busbars or connections having air, oil, solid or semi-solid materials as the principal insulation. When copper is used, hard-drawn bars are preferred to cold-rolled because of their better surface finish and because hard-drawing results in increased strength. Copper has a resistivity at 20°C. of about 1·76 microhms per cm. per sq. cm. section for drawn bar or 1·72 microhms for annealed bar, while aluminium has a resistivity of about 2·87 microhms per cm. per sq. cm. section. Both copper and aluminium sections are supplied dead to size within very close limits, the tolerances being given in a series of British Standards, of which B.S.1432 and B.S. 1433 apply for flat bars and round bars in copper and B.S.2898 for these sections in aluminium. The value of small tolerances lies mainly in the fact that switch blades (for example) can be made direct from the bar as recieved without machining.

CURRENT-CARRYING CAPACITY

At one time the current-carrying capacity of electrical conductors was based on the rule of 1 000 amperes per sq. inch. This rule was very rough and ready and led to the uneconomical use of material, particularly where the conductors were of small section and where densities well over 1 000 amperes per sq. inch could be used. The feature which should control the current-carrying capacity of a conductor is that of temperature and to this end B.S.159 states that the temperature rise of busbars and busbar connections when carrying rated normal current at rated frequency shall not exceed 50°C and that this rise is based on an ambient temperature having a peak value not exceeding 40°C and an average value not exceeding 35° measured over a 24-hour period.

Based on this it is clear that the temperature of any busbar or connection should not exceed 90°C. Above this figure oxidation increases rapidly and may give rise to cumulative and excessive heating at joints and contacts.

There are very many variables which affect the temperature to which a conductor will rise. In brief they include the number and arrangement of laminations, whether bars are on edge or laid flat, whether freely exposed to the air or surrounded by insulation, the proximity of a surrounding casing and the material of which the latter is made.

The amount of heat generated in a conductor is proportional to the resistance of that conductor and to the square of the current it carries, while the temperature rise depends on the rate at which the heat is dissipated, the latter taking place in varying degrees by convection, radiation and conduction.

Busbars completely surrounded by insulation will have the heat removed solely by conduction in the first instance, while bars freely exposed to the air will have the heat dissipated by convection and radiation. The maximum rate of heat dissipation with rectangular sections occurs when the sections are thin thus having a long perimeter for a given cross-sectional area. When a number of rectangular bars are arranged in parallel their current-carrying capacity is reduced because their surfaces will dissipate less heat, the various bars effectively shielding adjacent bars. Thus if the current-carrying capacity of a single rectangular section is known then that of a multiple bar can be determined approximately by multiplying by an appropriate factor from the following:—

D.C.		A.C.	
2 laminations	1·8	2 laminations 2 in. wide	1·74
3 ,,	2·5	2 ,, 3 ,, ,,	1·70
4 ,,	3·2	2 ,, 4 ,, ,,	1·66
5 ,,	3·9	3 ,, 2 ,, ,,	2·30
6 ,,	4·4	3 ,, 3 ,, ,,	2·20
8 ,,	5·5	3 ,, 4 ,, ,,	2·09
10 ,,	6·5	4 ,, 3 ,, ,,	2·45
		4 ,, 4 ,, ,,	2·30

Both the above sets of figures are given by the Copper Development Association as being applicable to bars $\frac{1}{4}$ inch thick and with $\frac{1}{4}$ inch spacing between laminations.

In the case of a.c., increasing the number of laminations does not greatly increase the current-carrying capacity because, as Fig. 14-1 shows, in a composite bar of ten laminations, the current density in the outer strips is about four times that in the centre strip. In general, a multiple bar of four or five laminations is an economical limit from a current-carrying point of view.

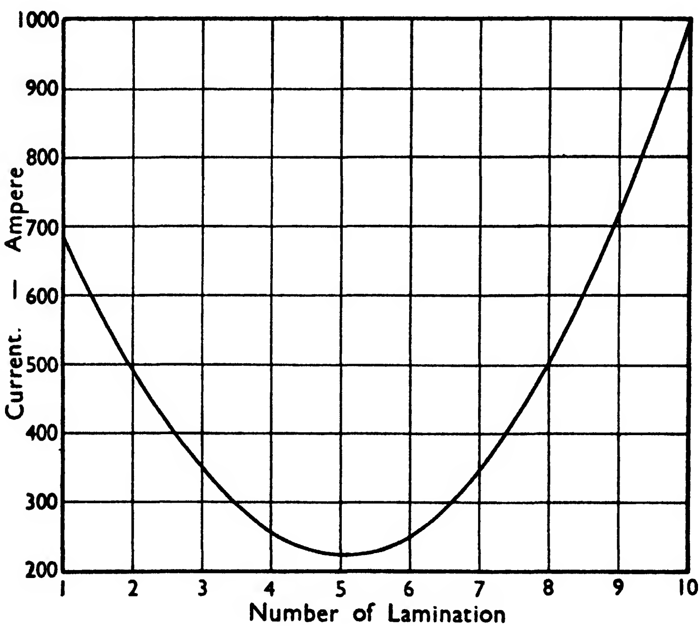


FIG. 14-1—*Alternating current distribution in a bar of ten laminations (C. F. Wagner, "Electrical World," Vol. 79 (1922)).*

Beyond this it pays to look at other formations and to illustrate this, Fig. 14-2 shows various formations for four square inches of conductor. The comparative a.c. ratings are given above the columns and it will be noted that as between the first and last columns there is a difference of 85 per cent.

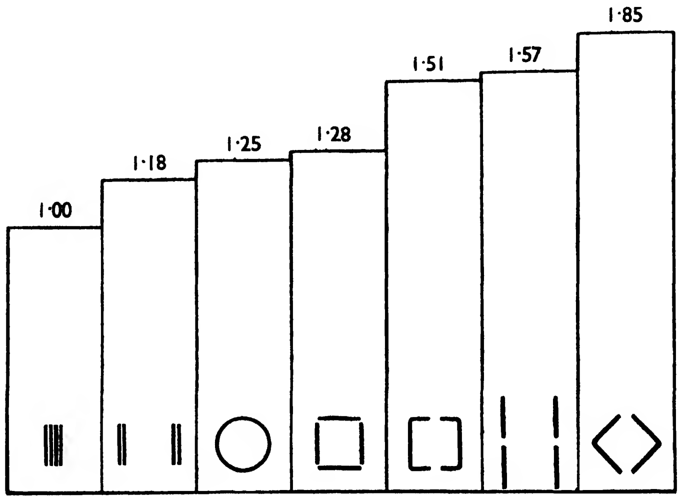


FIG. 14-2.—*Comparative a.c. ratings of various conductor arrangements of equal cross-section, i.e. four square inches (Copper Development Association).*

These relationships must however be regarded as approximate only, as much depends on the surroundings. The comparisons for example assume conductors freely exposed to the air and if they are enclosed then very different relative ratings might apply.

The determination of the actual current which a given section of conductor will carry and not exceed the temperature limits noted earlier is a matter of some complication. Formulae for the determination of the *direct current* carrying capacity of copper conductors have been given by the Copper Development Association as follows:—

Flat bars $I_{dc} = 678A^{0\cdot5} \cdot p^{0\cdot39}$

Round bars (solid) $I_{dc} = 1080A^{0\cdot68}$

where I_{dc} = Direct current in amperes.

A = Cross-sectional area in square inches.

p = Perimeter of conductor in inches.

These formulae assume a temperature rise of 50°C over an ambient of 30°C but it is stated that if used for a 40°C ambient, an error of about 1·5 per cent will probably be less than those implied by other assumptions

which, inevitably, must be made. If it is desirable to limit the temperature rise to a lower figure than 50°C, the following factors may be used:—

For 30°C rise multiply by 0·757

For 40°C rise multiply by 0·887.

For aluminium conductors, the following formulae have been advanced to determine the *direct current* carrying capacity.

Flat bars $I_{dc} = kA^{0\cdot45} \cdot p^{0\cdot5}$

Round bars $I_{dc} = kD^{1\cdot4}$

where I_{dc}, A and p are as for copper.

D = Diameter of rod in inches.

k = Constant as follows:—

Flat bars = 385 for a 40°C rise.

,, ,, = 438 for a 50°C rise.

Round bars = 659 for a 40°C rise.

,, ,, = 749 for a 50°C rise.

It is of interest here to note that the current carrying capacity of a bar can, without increase in temperature rise, be increased by about 20-25 per cent by painting the surfaces with a dull black paint (matt finish non-metallic).

Before leaving the question of direct-current ratings, it is well to note that Thomas and Rata make no endeavour to establish these ratings by the use of formulae in their book "Aluminium Busbar" (see bibliography) and make the following statement:—

"Several attempts have been made to establish the law connecting the current-carrying capacity with temperature and busbar shape in mathematical terms, notably by Melson and Booth, but it should be noted that their particular formula applies only to bars that are painted perfectly black and situated in still unconfined air. Further it deals only with one conductor per circuit and hence the majority of practical cases are not covered by the formula. Ratings for aluminium alloy busbar given in this book have been established by direct experiment and not by calaculation."

Busbars and conductors for use on a.c. systems require further study to establish a current-carrying capacity. This is due to the fact that whereas direct current distribution in a conductor is controlled only by the resistance of the various parts of the conductor, giving uniform current density regardless of shape or the position of return conductor, a conductor on a.c. is subject to inductive effects as well as resistance, leading to variations in current density over the section of the conductor, and to the fact that the current density may be distorted by the current in adjacent conductors. These two phenomena are known as "skin effect" and "proximity effect" respectively.

Skin effect is that effect which tends to crowd the current into the outlying parts of a conductor and is due to the back e.m.f. induced wherever an alternating flux exists by virtue of this flux cutting the conductor. This e.m.f. is produced in a bar by its own magnetic flux and while the central portions of the conductor are cut by the flux from all parts of the bar, the

outlying portions are not, the line linkages decreasing as the edges are reached. Current tends therefore to crowd into the edges of a flat strip, the outer members and edges of a multiple bar, and the skin of a circular bar, where the opposing e.m.f. is a minimum.

Proximity effect is due to the proximity of an adjoining or adjacent pole or phase. When a bar is cut by the flux from such adjoining or adjacent conductor, the current tends to crowd into the portion of the conductor nearest the other bar.

Both effects have one result—an increase in the apparent resistance of the conductors and as I^2R is the measure of the heat generated, the

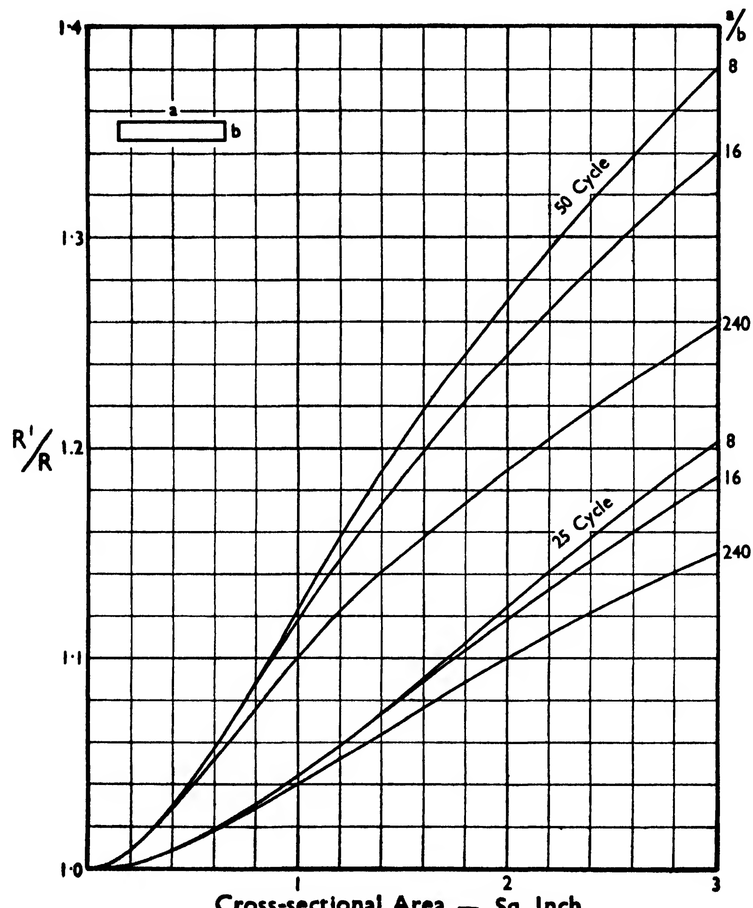


Fig. 14-3.—*Skin effect in rectangular high conductivity copper bars at 20°C (Copper Development Association).*

temperature rise of two bars of equal section carrying the same current will be higher for that bar carrying alternating current. For heavy current applications, both effects can be countered to some degree by careful consideration in the design and layout of the conductors. Skin effect, for example, can be reduced by adopting a form such as the "hollow square" or by using tubular bars. In both forms as much copper as possible is located equidistant from the magnetic centre of the bar. Proximity effect may be reduced by spacing the conductors to the maximum possible or by some special arrangement to ensure that no bar is adjacent to another.

When conductors are close together, as is often the case in low-voltage switchgear where the electrical clearances demanded are small, and in compound-filled busbar chambers, proximity effect can be pronounced. The problem of ratings is further complicated by reason of the fact that in perhaps the majority of switchgear designs, the conductors may be enclosed in non-magnetic or magnetic enclosures, each form having its own effect on the current rating of a conductor, resulting in some reduction in the "free air" rating.

An approximate value for the latter may be determined, for isolated flat bars, from the formula:—

$$I_{ac} = \frac{I_{dc}}{\sqrt{\frac{R^1}{R}}}$$

where R^1 = Apparent a.c. resistance.

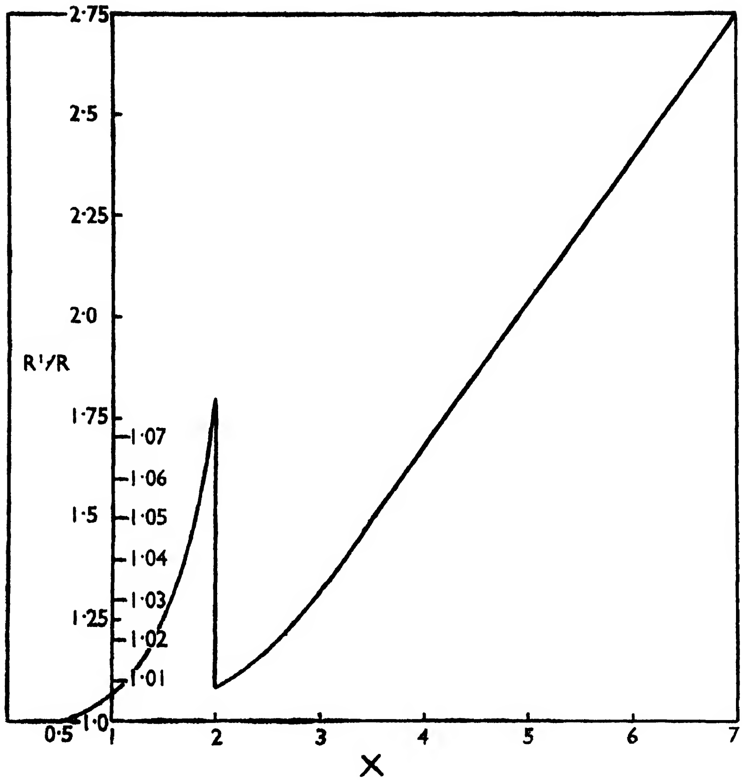
R = D.C. resistance.

and R^1/R is the skin effect ratio.

This ratio for rectangular bars may be read directly from the curves in Fig. 14-3 against cross-sectional area and for various ratio of width to thickness. Where this ratio is large the curves $a/b = 240$ should be used. The formula, it should be noted, applies only to isolated (i.e. single) flat bars and factors by which the value so determined should be multiplied for multiple bars have been noted on page 417. A study of the curves reveals that for all practical purposes in single flat copper bars up to about 0·5 sq. in. cross-sectional area, the a.c. current rating can be assumed to be equal to the d.c. rating. This is true also for copper rods up to about 0·75 sq. in.

In arriving at an a.c. rating by the formula given it has been assumed that the conductor is at such a distance from the return conductor that the effect of current in the latter can be neglected, i.e. the rating is not affected by proximity effect. The magnitude of this depends among other things, upon the frequency and on the spacing and arrangement of the conductors. This problem has been dealt with in some detail in the book "Aluminium Busbar" by Thomas and Rata and these authors state that "Proximity effect can safely be regarded as introducing a change of 5 per cent or less in the rating if the current is less than 2 000 to 3 000 amperes and the voltage exceeds 1 000 volts, because the busbar will not then be too large nor will the spacing be too close."

In the case of rod conductors, used with considerable advantage in certain designs of switchgear, and particularly at the higher voltages, the skin effect ratio R^1/R for copper is obtained from the curves Fig. 14-4.



Method of Use—

Calculate X from $X=0\cdot3065\sqrt{Af}$
Where A = Area of rod in sq. in.
f = Frequency in cycles.
From X on base line project vertically to curve and from point of intersection project horizontally to left to read ratio R^1/R
Where X is less than 2 use inset scale for R^1/R
This chart is adapted from Fig. 5 in "Copper for Busbars" (Copper Development Association)

FIG. 14-4.—*Skin effect in high conductivity copper rods at 20°C.*

Based on the foregoing data, Tables 14:1 to 14:4 which follow give the current ratings for a selection of sizes of rectangular bars and round solid rods.

TABLE 14:1

APPROXIMATE DIRECT CURRENT RATING (INDOORS) FOR H.C. COPPER STRIPS AND BARS

Dimensions	Amperes	Dimensions	Amperes
1" × 1/16"	225	6" × 1/4"	2 220
1½" × 1/16"	325	2" × 3/8"	1 080
1" × 1/8"	325	3" × 3/8"	1 520
1½" × 1/8"	470	4" × 3/8"	1 920
2" × 1/8"	590	5" × 3/8"	2 320
1" × 1/4"	485	6" × 3/8"	2 740
1½" × 1/4"	675	2" × 1/2"	1 270
2" × 1/4"	860	3" × 1/2"	1 770
2½" × 1/4"	1 040	4" × 1/2"	2 250
3" × 1/4"	1 220	5" × 1/2"	2 730
4" × 1/4"	1 560	6" × 1/2"	3 190
5" × 1/4"	1 900	8" × 1/2"	4 090

Ampere ratings are for single bars mounted on edge, freely exposed to still air and for a temperature rise of 50°C above an ambient of 30°C (see comment on page 418). For a 30°C rise multiply by 0·757. For a 40°C rise multiply by 0·887. For a.c. ratings see formula page 421. For multiple bars multiply by factors on page 417. This table extracted from Table 2 "Copper for Busbars" (Copper Development Association).

JOINTS

The first essentials for any joint that has to be made between busbar sections or between teed conductors and a busbar are (a) that it shall be mechanically strong and (b) it shall have a relatively low resistance at all times, i.e. its electrical efficiency should remain stable under all service conditions.

The simplest and most widely used method of making a joint is by bolting or clamping the sections together, a method which is simple and flexible, and allows the joint to be dismantled if required. Other methods include riveting, soldering or welding but in each of these the joint must be regarded as permanent.

TABLE 14:2

APPROXIMATE DIRECT CURRENT RATING FOR H.C. COPPER RODS

Diameter	Indoor amperes	Outdoor amperes	Diameter	Indoor amperes	Outdoor amperes
¼″	140	205	1½″	1 580	2 040
⅜″	240	340	1¾″	1 960	2 510
½″	360	485	2″	2 350	3 015
⅝″	480	645	2½″	3 190	4 080
¾″	620	810	3″	4 030	5 215
⅞″	760	990	3½″	5 020	6 435
1″	910	1 185	4″	6 040	7 710
1¼″	1 240	1 595			

Ampere ratings determined on the assumption that the conductor is mounted horizontally, freely exposed to the air and a temperature rise of 50°C above an ambient of 30°C (see comment on page 418.) For indoor installations still air conditions have been assumed. For a 30°C rise, multiply by 0·757 and for 40°C rise multiply by 0·887. For a.c ratings at 50 cycles see formula page 421. This table extracted from Table 3 "Copper for Busbars" (Copper Development Association).

In whatever method is employed, certain precautions must be taken to ensure efficiency, namely:—

(a) The contact pressure must be ample and be maintained.
(b) The conductor surface must be clean before the joint is made.
(c) For aluminium bars and bimetallic joints, air and moisture must be excluded.
(d) The overlap must be equal to or greater than the width of the busbar.

In passing it may be noted that while bolted joints are compact and reliable, they have the disadvantage that holes must be drilled or punched through the conductors thereby reducing the effective area. This is avoided if clamped joints are employed and because of the extra mass of metal surrounding the joint it is cooler in operation. The disadvantage is the extra bulk which becomes a nuisance in certain classes of gear with metal-enclosed busbars.

In the design of any joint the gross contact area is not of primary importance, for it has been established that current is transferred through the joint at numerous point contacts between irregularities on the contacting surfaces. It is well known that the number and effectiveness of these point contacts depends almost entirely on the pressure, and its distribution at the joint, whether by bolts or clamps. The effect of pressure on the contact resistance of a joint is demonstrated in Fig. 14-5, while the total pressures required per inch of width for joints to give 100 per cent efficiency are

TABLE 14:3

CURRENT RATINGS FOR NORAL D 50 SWP ALUMINIUM ALLOY RECTANGULAR BUSBARS

Size	1 Bar		2 Bars		3 Bars		4 Bars	
	D.C.	A.C. 50 c/s	D.C.	A.C. 50 c/s	D.C.	A.C. 50 c/s	D.C.	A.C. 50 c/s
	Amperes		Amperes		Amperes		Amperes	
1" × ¼"	356	356	718	715	980	970	120	1 100
1½" × ¼"	520	520	1 030	1 020	1 380	1 350	1 585	1 535
2" × ¼"	672	670	1 315	1 290	1 765	1 705	2 050	1 940
2½" × ¼"	820	812	1 550	1 510	2 100	2 000	2 430	2 260
3" × ¼"	970	958	1 805	1 740	2 440	2 310	2 860	2 620
4" × ¼"	1 260	1 235	2 260	2 140	3 060	2 800	3 640	3 200
5" × ¼"	1 545	1 505	2 700	2 510	3 660	3 240	4 410	3 700
6" × ¼"	1 840	1 780	3 130	2 860	4 290	3 680	5 250	4 240
2" × ⅜"	840	830	1 560	1 500	2 090	1 970	2 460	2 260
3" × ⅜"	1 210	1 180	2 180	2 050	2 940	2 660	3 510	3 030
4" × ⅜"	1 550	1 495	2 710	2 480	3 660	3 150	4 400	3 560
5" × ⅜"	1 940	1 860	3 290	2 930	4 450	3 660	5 400	4 200
6" × ⅜"	2 260	2 120	3 770	3 340	5 140	4 080	6 300	4 680
8" × ⅜"	2 940	2 750	4 800	4 150	6 500	4 900	8 060	5 740
3" × ½"	1 405	1 355	2 450	2 240	3 290	2 830	4 000	3 240
4" × ½"	1 830	1 740	3 100	2 720	4 170	3 360	5 100	3 900
5" × ½"	2 230	2 080	3 720	3 120	5 040	3 900	6 170	4 550
6" × ½"	2 620	2 420	4 300	3 500	5 850	4 400	7 200	5 100
8" × ½"	3 380	3 060	5 450	4 450	7 420	5 300	9 110	6 150
10" × ½"	4 080	3 640	6 500	5 000	8 860	6 000	10 900	6 850

Noral D 50 SWP (Magnesium Silicide Alloy) is the product of Alcan Industries Ltd. For their Noral CISM (99·5% pure aluminium) busbar, multiply by 1·03. The designations are proprietary ones for alloys corresponding to E91E and E1E materials to B.S. 2898.

Ratings are based on a 50°C rise over 35°C ambient temperature in still but unconfined air.

For multiple bars, the space between bars is equal to the bar thickness.

Bars assumed mounted vertically on edge and a.c. ratings are based on spacings at which proximity effect is negligible.

Ratings may be increased approximately 20% if the busbars are painted with non-metallic matt finish paint.

This table extracted from Table 2 "Aluminium Busbar" (see bibliography).

TABLE 14:4

CURRENT RATINGS FOR NORAL D 50 SWP ALUMINIUM ALLOY SOLID ROUND BUSBARS

Diameter	D.C. amperes	A.C. 50 c/s amperes
$\frac{3}{8}''$	155	155
$\frac{1}{2}''$	230	230
$\frac{5}{8}''$	335	335
$\frac{3}{4}''$	435	435
$\frac{7}{8}''$	550	548
1″	690	685
$1\frac{1}{4}''$	945	925
$1\frac{1}{2}''$	1 200	1 160

Noral D 50 SWP is the product of Alcan Industries Ltd. It is the proprietary alloy designation for E91E material to B.S. 2898.
Ratings are based on a 50°C rise over 35°C ambient temperature in still but unconfined air.
A.C. ratings are based on spacings at which proximity effect is negligible.
This table extracted from Table 5 "Aluminium Busbar" (see bibliography).

given in Fig. 14-6. This, then, is the real method of judging a joint, i.e., a method based on the clamping or bolting pressure. In designing to this method, however, it is essential that due regard be paid to the stresses set up in the bolts. It is usual that the latter will be of different material to the conductor and if the stress intensities in the materials of the joint are high when cold, they may be excessive when the joint is warm so that a permanent set in one part may arise. It should be borne in mind too that the bolts will not be at the temperature of the conductor since they are not directly heated by the current. Fig. 14-7 shows the approximate force per bolt for various sizes of bolts, and applies to bolts tightened with a spanner or wrench of normal dimensions, when used by an average workman.

The amount of overlap at joints is not dependent on the current transfer, because as previously indicated, the whole of the area is not effective in this respect. Rather, the overlap is determined by the number of bolts necessary to obtain the required pressure. The provision of a good overlap helps to preserve an efficient joint, particularly if coupled with the simple precaution of smearing the surfaces of the joint with vaseline, and scratch brushing just prior to making the joint.

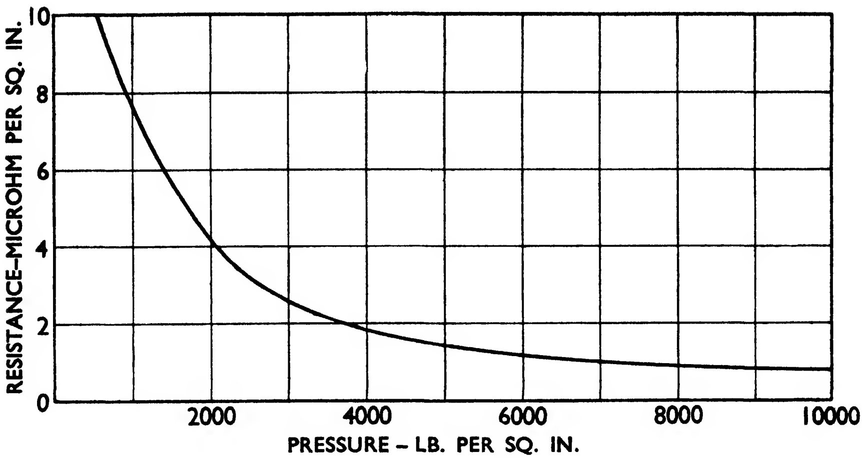


FIG. 14-5.—*Effect of pressure on the contact resistance of a joint between two copper conductors (Copper Development Association).*

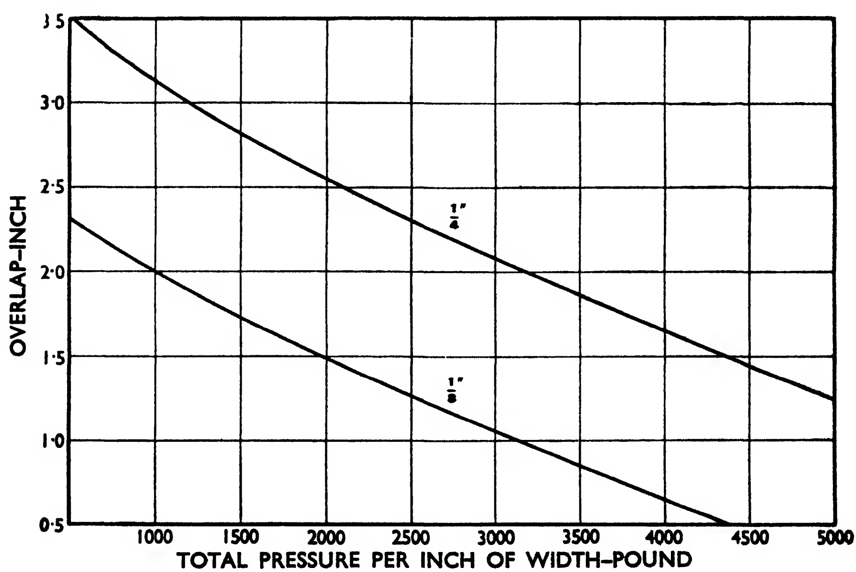


FIG. 14-6.—*Total pressures required per inch of width for joints to give 100% efficiency between flat copper strips $\frac{1}{8}$" and $\frac{1}{4}$" thick (Copper Development Association).*

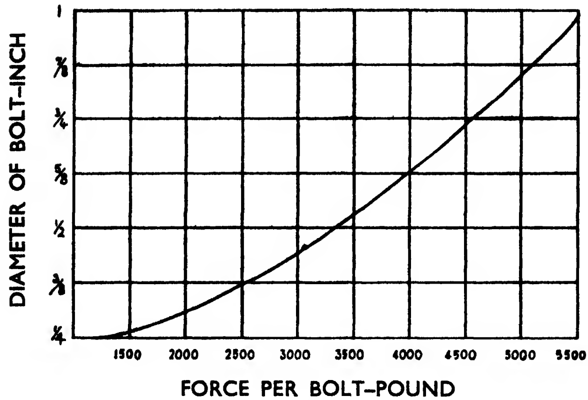


Fig. 14-7.—*The approximate force per bolt developed by bolts of various sizes (Copper Development Association).*

In some cases, where joint surfaces are very rough or where high current densities are unavoidable or where highly corrosive atmospheres exist, surfaces to be joined together may with advantage be tinned. If this is adopted the tinning should be done immediately before the joint is clamped or bolted up and it should be noted that both the electrical conductivity and the protective action of a lead-tin solder decrease as the lead content increases.

For joints between aluminium conductors a joint compound may be smeared on the faces before bolting up and one such compound has been recently developed by Aluminium Laboratories Ltd. specially for the purpose and is available under the trade name "Densal".*

If it is necessary to make a joint between a copper and an aluminium conductor, it has to be remembered that two dissimilar metals will be in electrical contact and if moisture is present electrolytic action will arise. The joint must therefore be made absolutely moisture proof using a grease as a joint compound or "Densal" as previously noted. Alternatively a bimetal connector may be introduced.

EXPANSION AND CONTRACTION

When there are variations of temperature there will be either expansion or contraction of the conductor and unless some provision is made to accommodate changes in length, particularly on long runs, some damage may be caused either to the conductor itself or to the supporting structure.

The co-efficient of the linear expansion of copper may be taken as 0·000017 per degree Centigrade and that of aluminium as 0·000023 per degree Centigrade.

* *Manufactured by Messrs. Winn & Coales Ltd. Denso House, Chapel Road, London, S.E.27.*

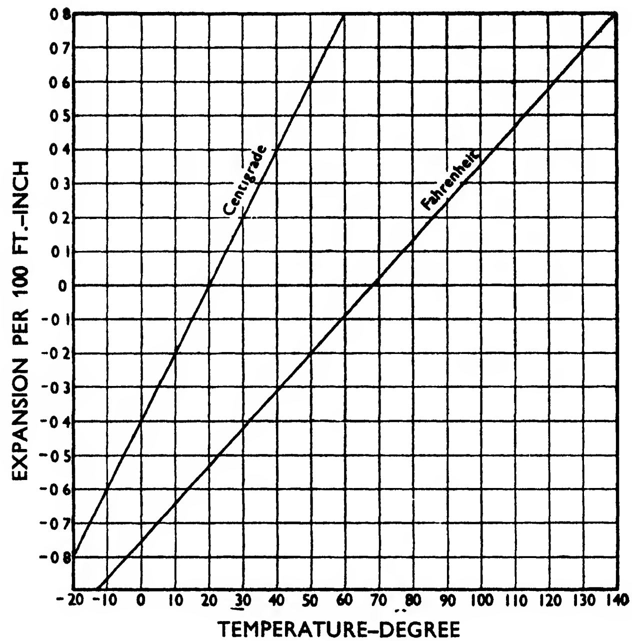


FIG. 14-8.—*Thermal expansion and contraction of copper conductors relative to their length at 20°C (68°F) (Copper Development Association).*

Fig. 14-8 gives curves to determine the expansion or contraction of copper conductors relative to their length at 20°C (68°F). Thus the total change in length per 100 feet of a copper conductor between temperatures of 0°C and 40°C will be 0·4+0·4= 0·8 inches. The expansion or contraction of a copper conductor relative to any temperature other than 20°C can be ascertained by drawing the line of zero expansion through the point of intersection of the curves and the ordinates corresponding to the temperature required.

In the case of very short bars, it is usually not necessary to make any special provision to accommodate expansion or contraction as within the normal temperature range the amount will be small and will be taken up by a certain amount of flexibility in the supporting structure. In other cases and where long rigid runs are involved, some form of expansion joint should be introduced at intervals, some typical joints being shown in Figs. 14-9 and 14-10.

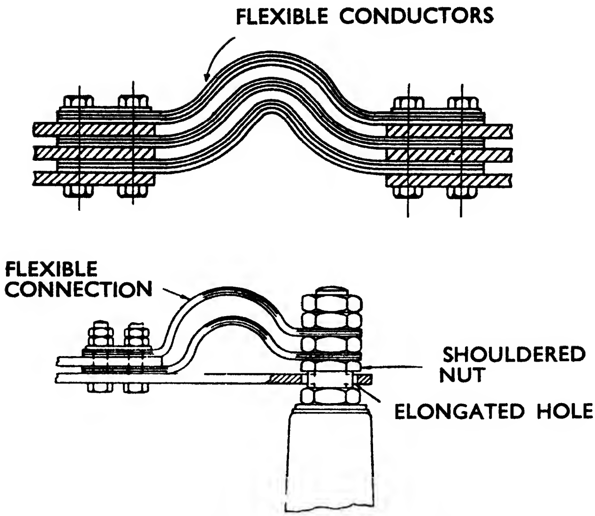


FIG 14-9 —*Forms of expansion joints*

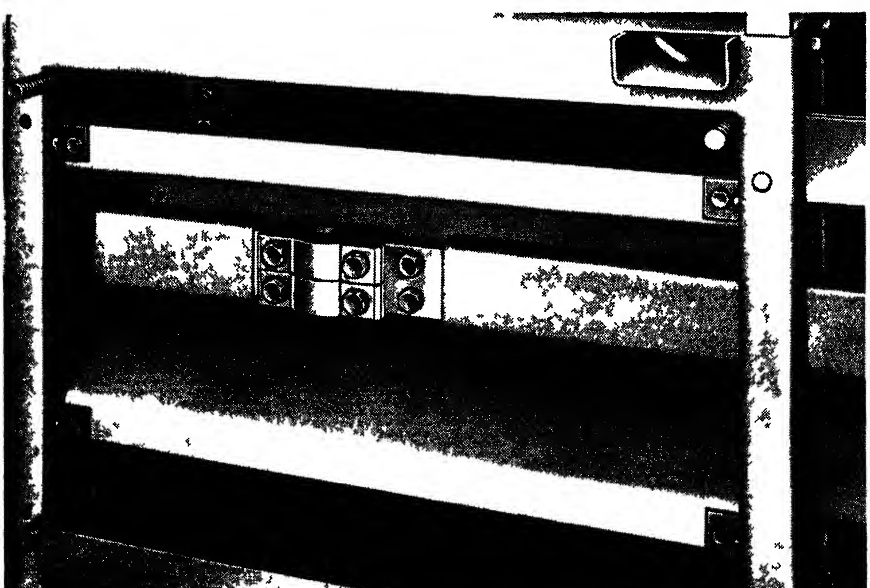


FIG 14-10 —*Expansion joint for 1 200 ampere busbars*

THE EFFECTS OF SHORT-CIRCUIT

In Chapters III and IV it has been shown how the current which can flow when a short-circuit occurs can be calculated. It was seen that the magnitude of these currents can be exceedingly high and clearly any busbar or connection system must in some way be affected by them.

The effects are two-fold. Firstly, the thermal effect which causes the conductor temperature to rise considerably due to the passage of the high value of current for a short period of time and secondly, the electromagnetic effect causing high forces of attraction or repulsion to be set up between conductors.

Dealing with the thermal problem first, it may be stated that this is related largely to the time the fault current is allowed to flow. What that time is will depend on the characteristics of the nearest automatic protective device which should operate to clear the fault.

If this device is a circuit-breaker the clearance time will depend largely on the form of protective gear and may vary from 0·02 to 0·5 or even 1·0 second.* If on the other hand the protective device is an h.r.c. fuse exhibiting a marked "cut-off" effect then the total clearance time may be as low as 0·005 seconds or less depending on the fuse link rating and the magnitude and degree of asymmetry of the fault current.

Because of various indeterminate but possible extensions of the total clearance time (sticky latching mechanisms for example) it is often expedient to allow for at least a clearance time of one second and sometimes more. B.S. 159 does in fact state: "The duration of the rated short-time current shall be:—

(i) 3-seconds where the ratio of the rated short-time current to the rated normal current is equal to or less than 40.

(ii) 1-second where the ratio of the rated short-time current to the rated normal current is more than 40."

In short times such as those noted it may be assumed that all the heat produced is absorbed by the conductor and that there is not time for it to be dissipated from the conductor by radiation or convection.

The thermal problem then is to determine the sectional area of the conductors to carry the calculated fault current for a defined time with a temperature rise which is safe not only for the conductor itself but for any insulation which may be in contact or in near contact and for sweated joints such as at cable sockets, etc. What this safe limit is, is a matter for decision taking all factors in a particular design into account and while some designers suggest a temperature rise of 175-200°C as being reasonable, others suggest a safer limit of 100°C. This latter figure has merit because it must be remembered that it is a rise above that at which the conductor may be running and this may well be 80-90°C so that with 100°C rise, a *total* temperature approaching 200°C is possible. It is worth pointing out here that solder which may be used at cable sockets will tend to soften at 180°C and at higher temperatures will run out.

There are therefore many arguments in favour of a reasonably low temperature rise although this can only be at the expense of more metal in the conductors.

**Where I.D.M.T. relays are used for the protection of ring main or other circuits (see Chapter XV), definite minimum tripping delays of up to 3 seconds may be imposed by the relays for discrimination purposes.*

An approximate formula for calculating the temperature rise in degrees C per second above an initial conductor temperature of 30°C, due to a known current is as follows:—

$$T = k \cdot \left(\frac{I}{A}\right)^2 \cdot 10^{-8}$$

where

T = Temperature rise per second, degrees C.
I = Current in amperes r.m.s. symmetrical.
A = Sectional area of conductor, sq. in.
k = 1·25 for copper; 2·8 for aluminium.

A more accurate formula would be:

$$T = k \cdot \left(\frac{I}{A}\right)^2 \cdot (1+\alpha\theta)\, 10^{-8}$$

where T = Temperature rise per second, degrees C.
I = Current in amperes, r.m.s. symmetrical.
A = Sectional area of conductor, sq. in.
α = Temperature coefficient of resistivity at 20°C. per °C.
= 0·00393 for copper.
= 0·00386. for aluminium
= 0·0036 for aluminium alloy.
θ = Temperature in degrees C of the conductor at the instant at which the temperatures rise is being obtained.
k = 1·25 for copper; 2·8 for aluminium.

This formula is not easy to use because of the difficulty of ascertaining θ.

Alcan Industries Ltd. have produced a series of curves, reproduced here at Fig. 14-11, from which the value—

$$I/A \cdot \sqrt{t}$$

can be deduced directly for a known initial temperature and a desired final temperature, for both copper and aluminium (Noral CISM).

These curves are based on the formula—

$$I\sqrt{t} = kA \sqrt{\log_e \left[\frac{1 + \alpha(\theta_F - 20)}{1 + \alpha(\theta_I - 20)}\right]}$$

where I = Current in kiloamperes r.m.s. symmetrical.
k = 146 for copper
96 for aluminium (Noral CISM).
92 for aluminium alloy (Noral D 50 WSP).
α = Temperature coefficient of resistivity at 20°C per °C (values as previously noted).
A = Sectional area of conductor, sq. in.
θ_I = Initial temperature degrees C.
θ_F = Final temperature degrees C.
t=time in seconds.

As an example of the use of these curves, let us assume that the essential data is:—

I = 46 kiloamperes.
t = 3 seconds.
θ_I = 20°C.
θ_F = 120°C (i.e. a rise of 100°C).

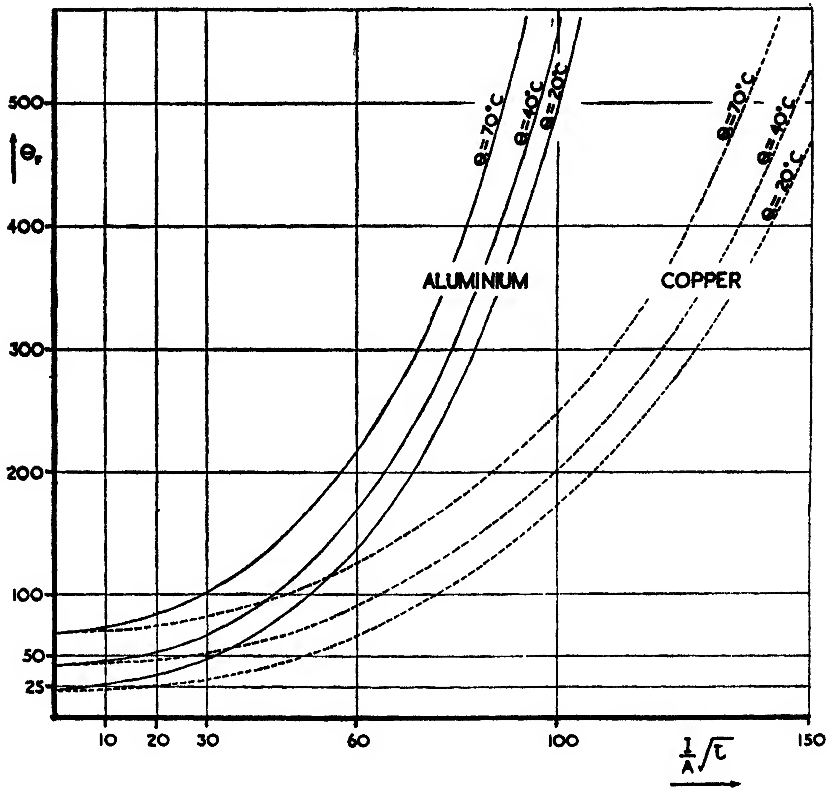


FIG. 14-11.—*Curves to determine conductor areas for a known initial temperature and any desired final temperature (Alcan Industries Ltd.).*

Projecting a line across from 120°C on the vertical scale to the point of intersection with the curve for copper at an initial temperature of 20°C and then from this point a vertical line to meet the horizontal scale of $I/A\sqrt{t}$ values at about 85, we get:—

$$\frac{46}{A} \cdot \sqrt{3} = 85$$

$$A = \frac{46 \cdot 1{\cdot}73}{85} = 0{\cdot}938 \text{ sq. in.}$$

For aluminium, the area required would be:—

$$\frac{46}{A} \cdot \sqrt{3} = 55$$

$$A = \frac{46 \cdot 1{\cdot}73}{55} = 1{\cdot}44 \text{ sq. in.}$$

In the book "Aluminium Busbar" Thomas and Rata have produced a series of nomograms from which, given the essential data as in the foregoing example, the conductor area may be read directly for copper, aluminium and aluminium alloy.

To consider now the electromagnetic problem it must first be appreciated that whereas in the thermal problem we were concerned with the r.m.s. symmetrical value of current and how long it lasted, here it is the *peak* current which occurs in the first half-cycle of short-circuit which determines the magnitude of the forces between adjacent bars. This peak current will have a value dependent on the degree of asymmetry and the power factor and where the latter is low (0·15 or less) then it may be 2·55 times the r.m.s. symmetrical value and for power factors of about 0·3, it will be 2·0 times.

Thus we find, taking one common example, that for a known short-circuit value of 31 MVA at 415 volts the short-circuit currents will be:—

Symmetrical r.m.s. amperes:	43 300
Initial peak amperes 0·15 PF	110 415
Initial peak amperes 0·3 PF	86 600

In all formulae to determine the forces set up under short-circuit conditions, it will be seen that the current value *has to be squared* so it is obvious, with the figures for the initial peak as indicated above, that the forces may be quite high. The design of the supporting structure must therefore be such as to ensure the safety of the busbars.

The formulae given in Fig. 14-12 are taken from the book "Aluminium Busbar" by Thomas and Rata, and a study of these will show that in the case of 3-phase alternating current systems, the worst condition is that of a fault between two lines (for calculation of such a fault see Chapter IV.)

All the formulae given are based on the assumption that the conductors are of circular cross-section and it is necessary to apply a correction factor when conductors of rectangular cross-section are used. This factor, denoted by the letter K is obtained from the curves in Fig. 14-13 from which it will be seen that the ratio $\frac{s-a}{a+b}$ has first to be calculated and then the value of K can be read from the curve for the correct ratio a/b. Having obtained K it is simply introduced as a multiplier into any of formulae in Fig. 14-12 thus:—

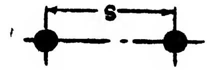
$$Fm = \frac{43{\cdot}2 \cdot 10^{-7} \cdot I^2 \cdot K}{S} \text{ lbs./ft. run}$$

A study of these curves will show that for bars spaced far apart, K approaches unity, and that while it is a maximum for very thin conductors, it is practically negligible for bars of square section.

That the forces due to short-circuit current can be substantial is shown in Table 14:5 where the approximate peak force in pounds per foot run is given for different values of MVA at 415 volts and based on the assumption of maximum asymmetry i.e. the r.m.s. symmetrical value of fault current as determined from short-circuit calculations has been multiplied by 2·55.

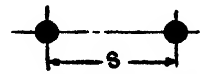
This table shows that by increasing the spacing between phases an easement in electromagnetic forces is obtained and although this is desirable in many ways, it can only be at the cost of larger busbar enclosures. It may be noted in passing that increasing the spacing will increase the reactance of the busbars (see Chapter III).

D.C. OR WHEN I_1 I_2 ARE INSTANTANEOUS VALUES OF A.C. CURRENT. IF THE CURRENT IN THE TWO BARS IS EQUAL, USE I^2 INSTEAD OF THE PRODUCT I_1 I_2.



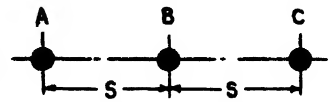
$$F = \frac{5{\cdot}4 \cdot 10^{-7} \cdot I_1\, I_2}{S} \text{ lb/ft.}$$

A.C. SINGLE PHASE CIRCUIT, FULLY OFFSET ASYMMETRICAL WAVE (CONDITION FOR MAXIMUM FORCE). ALSO SINGLE PHASE SHORT-CIRCUIT (LINE/LINE) ON A 3-PHASE BUSBAR.



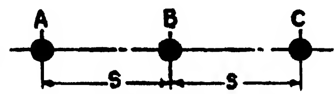
$$Fm = \frac{43{\cdot}2 \cdot 10^{-7} \cdot I^2}{S} \text{ lb/ft.}$$

A.C. THREE PHASE CIRCUIT, HORIZONTAL BUSBARS, FULLY OFFSET ASYMMETRICAL WAVE IN PHASE A (CURRENT WAVE CANNOT BE FULLY OFFSET IN ALL PHASES).



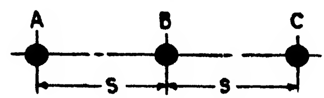
$$F = \frac{32{\cdot}4 \cdot 10^{-7} \cdot I^2}{S} \text{ lb/ft.}$$

A.C. THREE PHASE CIRCUIT, HORIZONTAL BUSBARS. CONDITIONS OF ASYMMETRY TO GIVE MAXIMUM FORCE ON OUTSIDE PHASE A OR C.



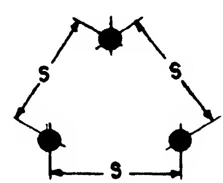
$$Fm = \frac{34{\cdot}9 \cdot 10^{-7} \cdot I^2}{S} \text{ lb/ft.}$$

A.C. THREE PHASE CIRCUIT, HORIZONTAL BUSBARS. CONDITIONS OF ASYMMETRY TO GIVE MAXIMUM FORCE ON CENTRE PHASE B.



$$Fm = \frac{37{\cdot}4 \cdot 10^{-7} \cdot I^2}{S} \text{ lb/ft.}$$

A.C. THREE PHASE CIRCUIT WITH EQUILATERAL TRIANGULAR BUSBARS. CONDITIONS OF ASYMMETRY TO GIVE MAXIMUM FORCE ON ANY PHASE.



$$Fm = \frac{37{\cdot}4 \cdot 10^{-7} \cdot I^2}{S} \text{ lb/ft.}$$

F = Force between conductors in lbs per foot.
Fm = Force obtained when conditions of asymmetry are such that the maximum possible force is obtained (lb/ft.).
I = r.m.s. current in conductors (amperes) (the factor representing the peak value of the wave in terms of the r.m.s. value for maximum asymmetry is contained in the numerical term of the force equation. Hence the r.m.s. value of current should be used in all calculations).
I_1 I_2 = Current in conductors 1 and 2 where they are different (amperes).
S = Spacing between conductors (centre to centre) inches.

Formulae are correct for circular conductors and correction factor should be applied for rectangular conductors—see page 434 and Fig. 14-13.

FIG. 14-12.—*Formulae for calculating the instantaneous peak short-circuit forces (Alcan Industries Ltd.).*

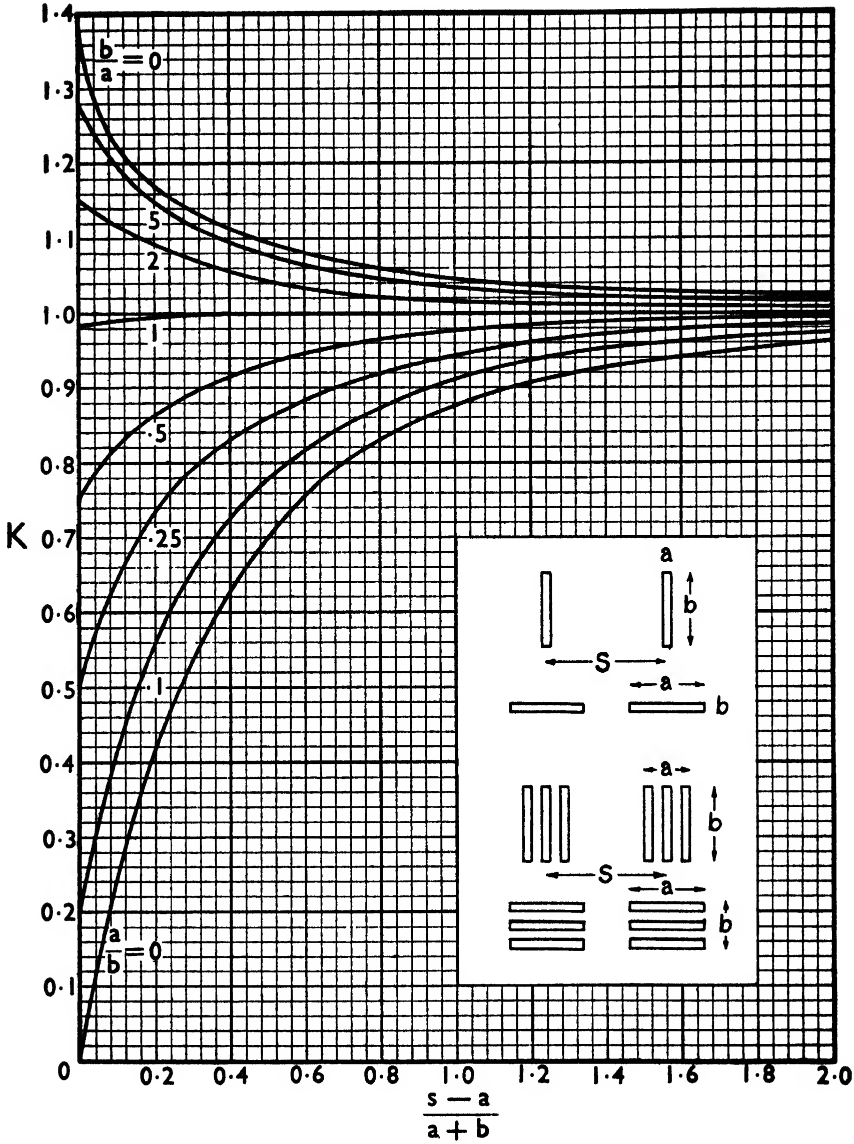


FIG. 14-13.—*Shape factor for rectangular conductors* (*The Copper Development Association*).

TABLE 14:5

ELECTROMAGNETIC FORCES ON BUSBARS OF RECTANGULAR SECTION, MOUNTED ON EDGE, AND IN HORIZONTAL PLANE

Spacing (centres)	MVA					
	10	15	20	25	30	35
Ins	Approximate peak force in lbs. per foot run					
1	600	1 325	2 460	3 670	5 300	7 200
3	200	440	820	1 200	1 770	2 400
5	120	260	490	730	1 060	1 440
7	85	190	350	520	760	1 030
9	65	145	270	400	590	800

CLEARANCES

The following tables 14:6, 14:7 and 14:8 are taken from B.S. 159: 1957 (Busbars and Busbar Connections) which should be consulted for other tables relating to open outdoor gear from 22kV to 275kV and for notes on the special circumstances relating to electrically exposed systems, i.e. systems in which the apparatus is subject to over-voltages of atmospheric origin.

TABLE 14:6

CLEARANCES FOR OPEN AND ENCLOSED INDOOR AIR-INSULATED BUSBARS AND CONNECTIONS ELECTRICALLY NON-EXPOSED

Rated voltage	Minimum clearance to earth in air		Minimum clearance between phases in air	
kV	Open inches	Enclosed inches	Open inches	Enclosed inches
Up to and including: 0·415	$\frac{3}{4}$	$\frac{5}{8}$	1	$\frac{3}{4}$
0·60	1	$\frac{3}{4}$	$1\frac{1}{4}$	$\frac{3}{4}$
3·3	2	2	2	2
6·6	$2\frac{1}{2}$	$2\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$
11	3	3	5	5
15	4	4	$6\frac{1}{2}$	$6\frac{1}{2}$
22	$5\frac{1}{2}$	$5\frac{1}{2}$	$9\frac{1}{2}$	$9\frac{1}{2}$
33	$8\frac{3}{4}$	$8\frac{3}{4}$	14	14
Note: Indoor type equipment for electrically exposed installations requires special consideration.				

TABLE 14:7

CLEARANCES FOR OPEN OUTDOOR BUSBARS AND CONNECTIONS NOT EXCEEDING 15kV RATED VOLTAGE FOR ELECTRICALLY EXPOSED OR NON-EXPOSED INSTALLATIONS

Rated voltage	Minimum clearance to earth in air	Minimum clearance in air between phases
kV	Inches	Inches
6·6	5½	7
11·0	7	9
15·0	8½	10½

Note: The above clearances are to be regarded as minimum values which may be used in any circumstances. Where the method of mounting insulators is not such as to prevent lodgement of birds or vermin, it may be necessary to employ larger clearances.

TABLE 14:8

CLEARANCES FOR BUSBARS AND BUSBAR CONNECTIONS IMMERSED IN OIL OR COMPOUND

Rated voltage	Minimum clearance to earth	Minimum clearance between phases
kV	Inches	Inches
Up to and including: 0·66	½	½
3·3	½	¾
6·6	¾	1
11	1	1½
15	1¼	1¾
22	1¾	2½
33	2½	3½

BIBLIOGRAPHY

B.S. 159. Busbars and Busbar Connections.

B.S. 162. Electric Power Switches for indoor and outdoor installations up to and including 22,000 volts.

Aluminium Busbar, A. G. Thomas and P. J. H. Rata (Hutchinson Scientific & Technical for Alcan Industries Ltd).

Aluminium Busbars and Connections, The British Aluminium Co., Publication No. 393.

Copper for Busbars, The Copper Development Association, Publication No. 22.

Electric Switch and Control Gear, C. C. Garrard (Benn Brothers).

The Calculation and Design of Electrical Apparatus, W. Wilson (Chapman and Hall).

The Switchgear Handbook, Vol. 1, W. A. Coates and H. Pearce (Sir Isaac Pitman and Sons, Ltd.).

"Electromagnetic Forces Set up Between Current-Carrying Conductors During Short-Circuit," G. L. E. Metz, "Journal I.E.E.," Vol. 75, No. 454, October, 1934.

"Forces on Conductors During Short-Circuit," W. R. Tripp, "The Electric Journal," December, 1937.

"Skin Effect in Tubular and Flat Conductors," H. B. Dwight, "Journal A.E.I.E.," 1918, page 977.

"Temperature Rise of Busbars," H. B. Dwight, G. W. Andrew and H. W. Tileston, "General Electric Review," May, 1940.

"The Current-Carrying Capacity of Solid, Hard Copper and Aluminium Conductors," Melson and Booth, "Journal I.E.E.," Vol. 62, No. 335, November, 1924.

"The Rating of Copper Conductors," A. Bannister, "Metropolitan-Vickers Gazette," September, 1934.

CHAPTER XV

PROTECTIVE GEAR

CHAPTER XV

PROTECTIVE GEAR

When anything abnormal occurs in the apparatus, cables or overhead lines of an electrical system, some action is necessary to isolate the abnormal condition either instantaneously or, in some circumstances, after a predetermined time delay. Such action must be automatic and selective, i.e. it must segregate the faulty section or piece of equipment leaving the healthy remainder in normal service. This is the function of protective gear which, in one form or another, is designed to sense the presence of dangerous conditions and based on this sensing, to isolate the circuit.

In very broad terms, the abnormal conditions against which protection is required may be summarised as follows:—

(a) The condition of overloading which, if persistent, leads to overheating of transformer or machine windings and cables or damage to other plant.

(b) The failure of insulation to an extent where a dangerous leakage of current can occur to earth.

(c) The faulure of insulation to the extent where a short-circuit occurs between two or three phases.

(d) The loss of, or a serious drop in, system voltage causing, for example, motors to stop.

In the case of conditions (b) and (c) external events may produce similar results, e.g. if vermin obtain access to bare conductors.

Many electrical circuits can be given adequate protection against these conditions by the application of relatively simple trip coils or relays but these have limitations which lead to the need for more complex and special protective schemes, examples of which are those applied to highly interconnected power systems such as the "Grid" system in Great Britain. For our purpose here it is convenient to consider first the simpler schemes and follow with some details of those of greater complexity. In passing we may note that perhaps the simplest of all protective devices is the fuse, types of which can be used either to cover *both* conditions (a) and (c) or to cover *mainly* condition (c). These alternatives have been considered in a fairly full discussion on the l.v. fuse as a protective device in Chapter XII and, to a lesser extent, in Chapter XVIII on h.v. fuses, so that further discussion here is unnecessary.

It is doubtful whether the fuse will act as a protective device for condition (*b*) as so much depends on the resistance of the earth circuit and, even in good initial circumstances, deterioration can occur. Given a very low value of earth path resistance, fuses of relatively low normal current rating (probably not exceeding 80 amperes) can give a degree of *earth-fault* protection but will not give any against *earth-leakage* where it is required to detect small values of current.

Next in order of simplicity is the direct-acting overload trip coil which, with some limitations which will be noted, can protect simple feeder or motor circuits against the abnormal conditions (a) and (c). In certain types of switchgear, mainly in the medium-voltage range, these coils can be of the series or whole current patterns, in which the coil is connected in series with the main circuit. Operating on the electromagnetic principle the coil acts as a solenoid with a central plunger, the latter being free to lift under electromagnetic influence to impinge on the circuit-breaker trip mechanism. There are, however, certain limitations as to the use of this type of coil, the first being that for high currents the production of a single-turn coil having sufficient conductor section is not easy—in one design for 800 amperes such a coil has been produced by suitably machining a solid block of copper—and the second being that at low currents a large number of turns of small cross-sectional area are necessary and such a coil is subjected to greatly increased stresses (electromagnetic and thermal) on the passage of short-circuit current. How coils of the latter type can affect the overall interrupting ability of a circuit-breaker has been noted in Chapter VI.

When these limitations apply and always in higher voltage switchgear, the direct-acting trip coil may be arranged for operation from the 5 ampere (or 1 ampere in some cases) secondary of a current transformer, the primary winding of which will be suited to the normal current rating of the circuit.

This arrangement virtually isolates the trip coil from the primary circuit, the coil being completely relieved of stresses under short-circuit conditions as, at heavy currents, the transformer will saturate to place a limit on the secondary current. A further advantage is that should the normal rating of the primary circuit be changed, it may only be necessary to change the current transformers, the trip coil remaining undisturbed.

In both types of direct-acting trip coil, the operating current value is usually adjustable either by varying the magnetic gap or, in some designs, modifying the tension of a restraining spring. Calibration markings will be provided to indicate the various setting points, varying from the lowest coinciding with the rated normal current to the highest at three times this value.

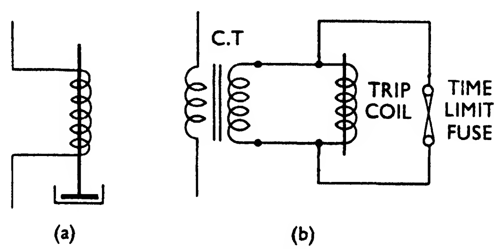
If no other steps are taken, trip coils of either type will operate practically instantaneously as soon as the current reaches the setting value. In a majority of circuits this is unwarranted and, indeed, in some cases where switching-in current surges occur, instantaneous operation would make it impossible to switch in a transformer or start a direct-on-line motor. All electrical apparatus can withstand some degree of overloading for a short time without damage, the heavier the overload the shorter the time it can safely be sustained. It is desirable, therefore, that some form of time delay device be added to the trip coil assembly which will give long delay times (relatively) at low values of overload, and shorter (maybe instantaneous) delay times as the current increases to short-circuit values. In other words, the retarding device should have an inverse time/current characteristic.

This may be achieved in two ways. Firstly, when a series connected overload trip coil is used, an oil dashpot can be attached in which is a piston connected to the lower end of the solenoid plunger. This piston, immersed in oil, provides the retardation element in such a way that the time of

operation is related to the pull on the plunger, this pull being directly related to the current in the coil.

When the trip coil is transformer operated, time delay is obtained by connecting a time limit fuse across the trip coil terminals, i.e. in parallel. This fuse should have an inverse time/current characteristic and will normally carry the current transformer secondary current to by-pass the trip coil. As and when sufficient current occurs to "blow" this fuse, the whole current is then transferred to the trip coil which operates to trip the breaker.

The foregoing discussion is illustrated by the single line diagrams Fig. 15-1.



(a) SERIES (WHOLE) CURRENT TRIP COIL WITH OIL DASHPOT TIME LAG.
(b) CURRENT TRANSFORMER OPERATED DIRECT-ACTING TRIP COIL WITH TIME-LIMIT FUSE.

FIG. 15-1.

Reverting for a moment to the oil dashpot form of time delay it may be noted that for use in temperate climates and where there is no wide range of operating temperatures, a mineral oil of suitable characteristics may be used satisfactorily in the dashpot. Such oils, however, have a rather steep viscosity/temperature curve, i.e. as the temperature rises so the oil becomes less viscous and there can be a significant reduction in the time delay property. This is particularly important if the apparatus is to be used in tropical or sub-tropical climates when high ambient temperatures can exist and possibly vary over wide limits, where normal oils may have so diminished in viscosity as to give little or even no time delay. One solution to this problem lies in the use of a silicone fluid which has a relatively flat viscosity/temperature characteristic when compared with that of mineral oil, a point demonstrated in Fig. 15-2.

The simple nature of the direct-acting trip coil is such, however, as to make it unsuitable in certain circumstances as for example where a high degree of accuracy in both current and time settings is essential or where two or more circuit-breakers in series are required to trip discriminatively. Accuracy may not be too important in many circuits and relatively wide tolerances can be accepted. The need for discriminatory tripping on the other hand may arise in even the simplest of systems such as that shown in Fig. 15-3 where one incoming feeder with 400 ampere overload coils gives supply to two outgoing feeders each with 200 ampere coils.

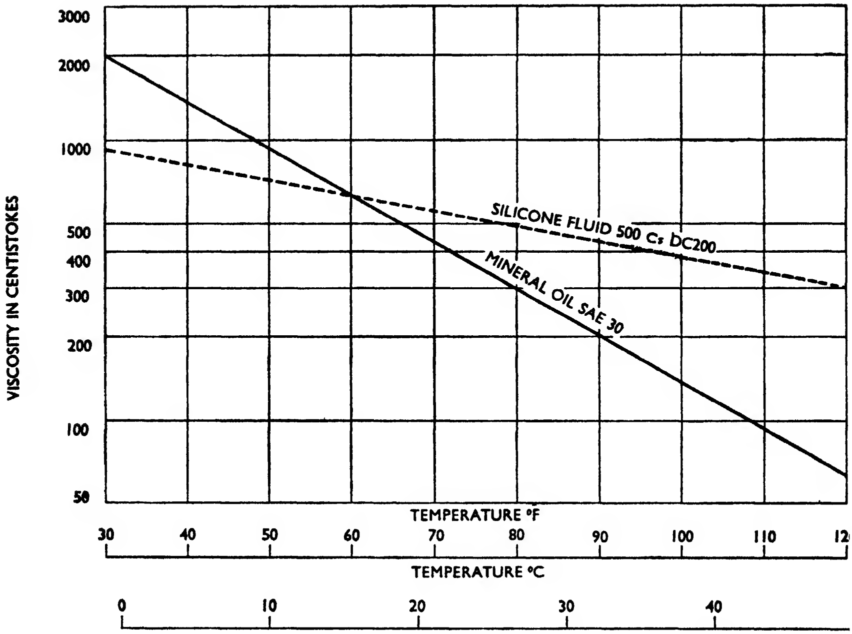


FIG. 15-2.—*Showing relative variation in viscosity with temperature change between silicone fluid 500 Cs DC200 and mineral oil SAE 30.*

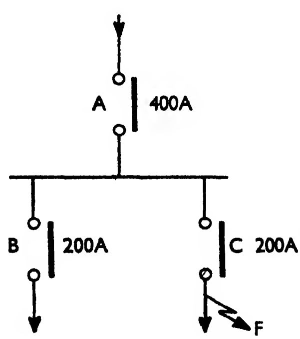


FIG. 15-3.—*Simple series circuits.*

If we assume that a fault occurs on feeder C as marked F, it is clear that the resultant current will flow through the two circuit-breakers A and C in series and unless the time delay on A exceeds that on C by a safe margin, both breakers will open. This, of course, is not necessary as to clear the fault only breaker C need be opened, leaving A closed to maintain the supply to feeder B. To ensure discrimination, the time delay at A should be at least 0·2 seconds longer than at C for the same value of current but when the latter is of short-circuit magnitude it is unlikely that any difference can be achieved and both will operate instantaneously.

This problem can be solved by the use of special time delay devices but much more satisfactory results are obtained by the use of relays which have an inverse definite minimum time delay characteristic and which provide, incidentally, a very high degree of accuracy in relation to both current and time settings. It must be noted, however, that the employment of a separate relay requires additional tripping facilities at the circuit-breaker, arranged to be energised from a separate source of supply, e.g. a 30 volt tripping battery as shown in Fig. 15-4(a).

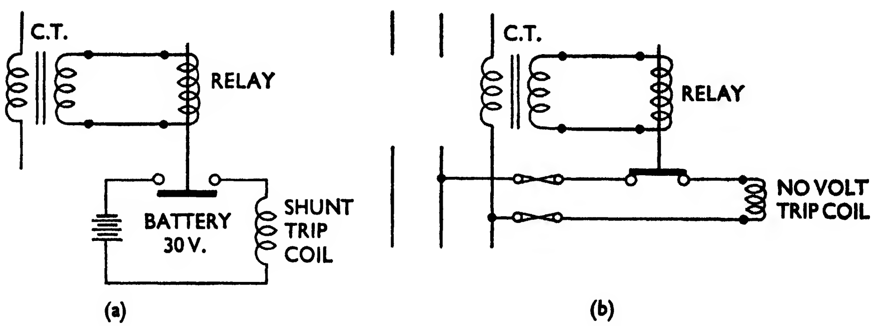


FIG. 15-4.—*Circuit-breaker tripping schemes when protective relays are used.*

Here it will be seen that when the relay operates to close its contacts, the circuit to the trip coil is completed and a plunger is lifted to act on the trip mechanism of the breaker. When a circuit-breaker in a particular part of a system is fitted with a no-volt trip coil, this may be used instead of the shunt type coil and battery, the contacts on the relay in such case being arranged to *open* on operation and open-circuit the no-volt coil as in Fig. 15-4(b). A further alternative is to arrange a current transformer operated direct-acting trip coil which is normally short-circuited by a pair of contacts on the relay as shown in Fig. 15-5. Operation of the relay opens these contacts to remove the short-circuit and the full current transformer output is now passed to the trip coil to operate the circuit-breaker.

The inverse definite minimum time relay (known as I.D.M.T. for brevity) has a characteristic time/current curve based on standard values given in Table No. 7 of B.S. 142 : 1953 and reproduced here as Fig. 15-6.

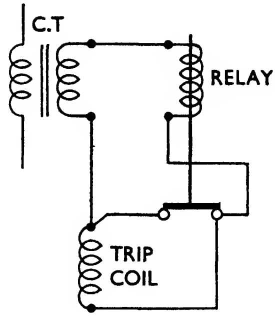


FIG. 15-5.—*Relay and trip coil wired for series tripping.*

This basic curve shows that when the current reaches short-circuit magnitude, no further reduction in operating time occurs below about 2·2 seconds, i.e. it has a definite minimum time of operation. The relay is fitted with an adjustment known as the "time multiplier", a device which controls the position to which the rotor in the relay resets after operation and thereby determining the travel the rotor has to make before it closes its associated contacts. This adjuster has a scale marked from 0·05 to 1·0 and it is at this latter value (unity time multiplier) that the curve in Fig. 15-6 is representative. Thus, if at unity time we obtain a definite minimum of 2·2 seconds, at 0·5 on the time multiplier we shall get a definite minimum

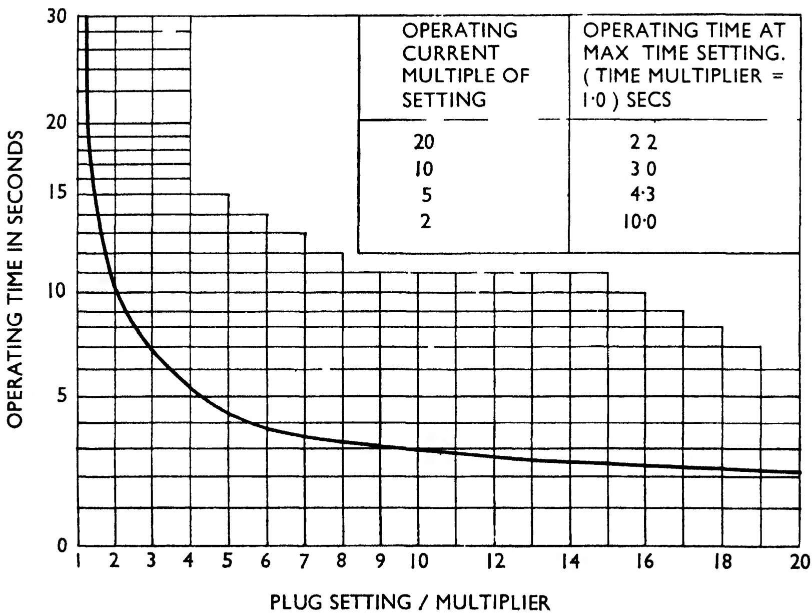


FIG. 15-6.—*Basic time/current characteristics of I.D.M.T. relay.*

of 1·1 seconds and at 0·05 obtain 0·11 seconds definite minimum. This gives, therefore, a range of definite minimum times of 0·11 to 2·2 seconds and with a number of relays in series, using a different time multiplier for each, discrimination can be obtained between them regardless of the current magnitude.

In practice it is essential that the difference in definite minimum times between adjacent series relays shall be such as to cover the operating and arcing time of the circuit-breaker clearing the fault, an allowance for relay over-run and a further allowance for manufacturing tolerances. These factors may quite easily account for a total time of about 0·4 seconds and for safety, a difference between series relays of 0·5 seconds is often employed. This means that with a range of definite minimum times of 0·11 to 2·2 seconds, not more than five relays will be possible in series and, because of this, relays can be obtained having higher upper limits, e.g. 4 seconds, thus permitting the use of more relays in series.

In some circumstances, the differential of 0·5 seconds can safely be reduced as for example when it is known that the circuit-breaker has a high-speed clearance time (0·2 second has been assumed for this in our value of 0·5 second) or when the relays have an over-run time less than the permissible 0·1 second given in B.S. 142.

For the purpose of demonstration, however, it will be assumed that a difference of 0·5 second is allowed as between the I.D.M.T. relays associated with circuit-breakers A, B, and C in Fig. 15-7. Using time multipliers of 1·0, 0·75 and 0·5 respectively for relays R_1, R_2 and R_3, we obtain three time-current curves as shown and indicating that for a fault at F_1, relay R_3

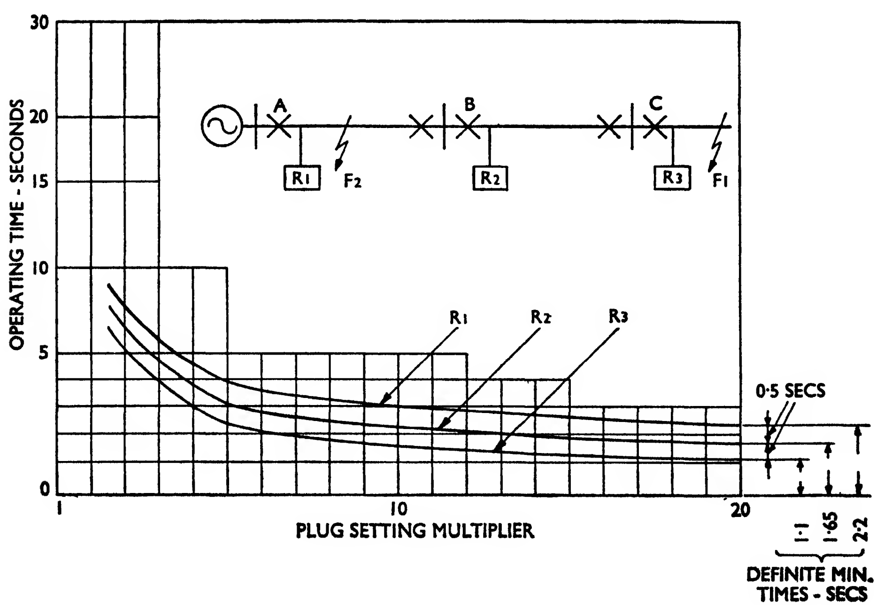
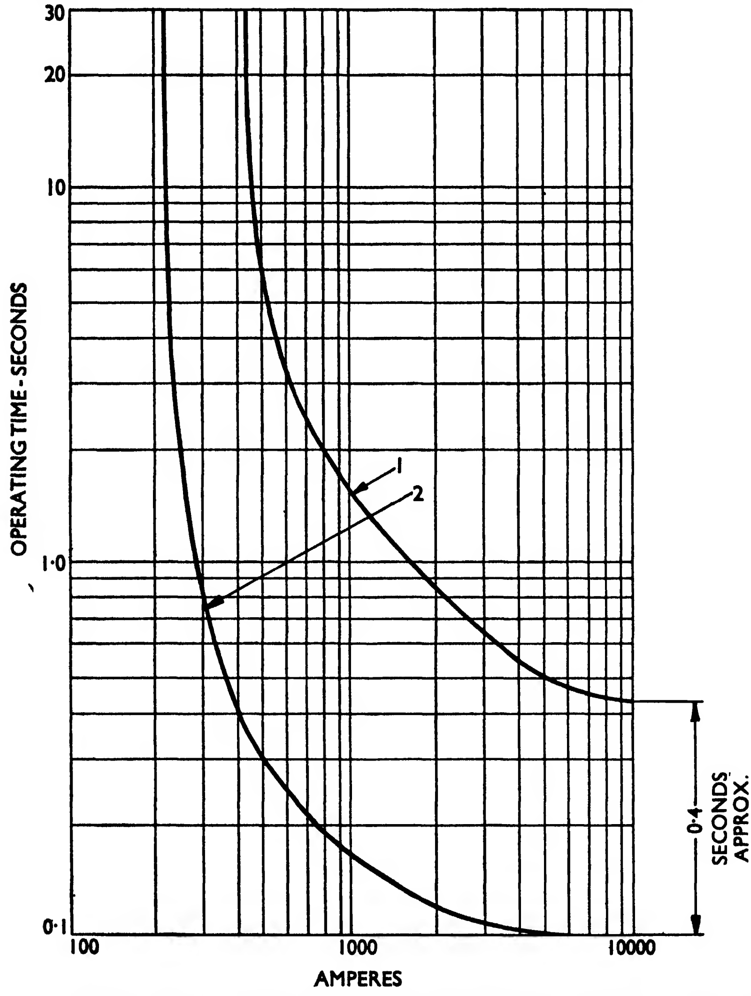


FIG. 15-7.—*Showing time-grading between relays in series.*

and circuit-breaker C will operate to clear the fault leaving breakers B and A in service.

Reverting to Fig. 15-3, it would be permissible to apply an I.D.M.T. relay at circuit-breaker A and ordinary direct-acting magnetic overloads with oil dashpot time-lags at circuit-breakers B and C provided that the correct time discrimination is maintained at maximum fault level. Typical time/current characteristics would be similar to those in Fig. 15-8.



CURVE 1 TIME/CURRENT CURVE FOR I.D.M.T RELAY AT BREAKER A FIG 15-3
CURVE 2 TIME/CURRENT CURVE FOR SOLENOID OVERLOAD COIL WITH OIL DASHPOT ON BREAKERS B & C FIG. 15-3

FIG. 15-8.—*Discriminating time/current curves for overload protection–breakers in series.*

The operating coil in an overcurrent I.D.M.T. relay is tapped to correspond to different current settings, usually covering the range 50-200% in seven equal steps although other ranges are available. The tappings are brought out to a plug bridge (shown in Fig. 15-9) for easy selection, and for any current above that chosen, the rotor will rotate and complete a pair of contacts in the breaker trip coil circuit at the end of its travel. At currents less than the setting, movement is prevented by a restraining spring.

Thus, this current setting device enables discrimination to be maintained at low overloads where two circuit-breakers in series have current transformers of the same ratio.

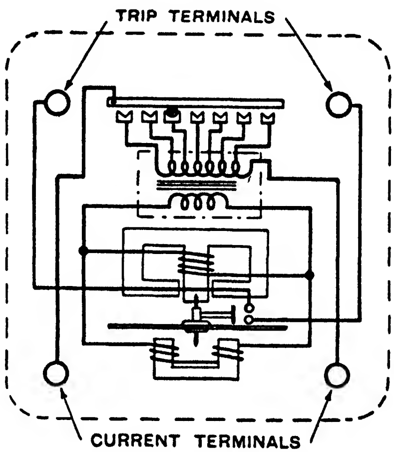
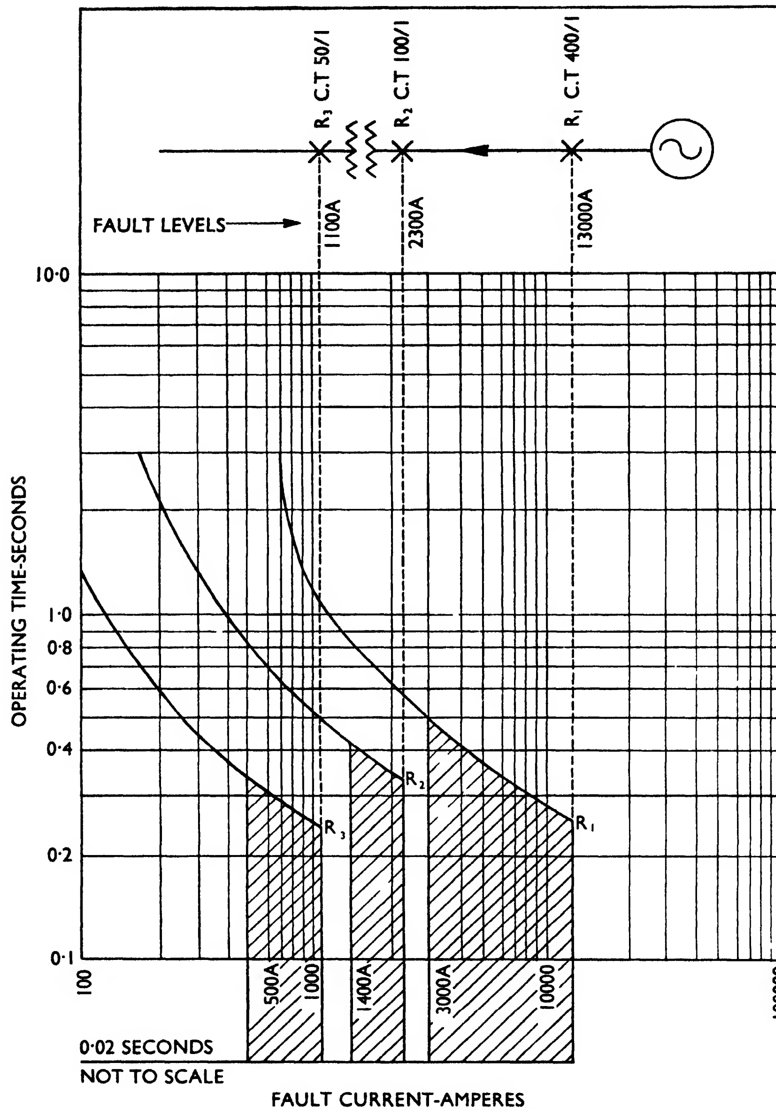


FIG. 15-9.—*Connections for non-directional I.D.M.T. relay.*

If we refer back to Fig. 15-7 and recall what has been demonstrated in Chapters III and IV, it will be clear that the value of fault current at F_1 will be determined by the impedance of the generator plus that of the intervening cables or overhead lines between breakers A and C. If we now assume the fault to occur at F_2 however, the only impedance is that of the generator and therefore the fault current can be considerably greater. Because relay R_1 at breaker A has the longest time characteristic, this heavier fault current will be maintained for a relatively long period unnecessarily. To overcome this disadvantage, relay manufacturers have developed an instantaneous overcurrent element which can be added to the normal I.D.M.T. relay and which can be set to give instantaneous tripping at high values of overcurrent, for example at 20 times normal full-load and operating in 0·02 seconds, instead of waiting for the I.D.M.T. relay to operate. It will be obvious that this high set instantaneous relay element to override the inverse relay at specified current values can be applied equally to relay R_2 and R_3, the current setting getting progressively lower as we leave the source of supply. It can be applied also to transformer feeders such that for faults on the primary side of the transformer, the instantaneous element



I.D.M.T. RELAYS ALL SET AT 125%	INSTANTANEOUS HIGH SET RELAYS
R1 SET AT 500 A ON 0·125 T.S.M.	R1 SET AT 3000 A
R2 SET AT 125A ON 0·15 T.S.M.	R2 SET AT 1400A
R3 SET AT 62·5A ON 0·1 T.S.M.	R3 SET AT 500A

T.S.M.=TIME SETTING MULTIPLIER

NOTE: THE EFFECT OF THE INSTANTANEOUS ELEMENT IS TO REDUCE THE OPERATING TIME IN THE SHADED AREAS TO 0.02 SECOND THUS GIVING HIGH-SPEED OPERATION OVER A LARGE PORTION OF THE CIRCUIT.

FIG. 15-10.—*Characteristics of combined I.D.M.T. relays and high set instantaneous relays. (Based on Fig. 3 of the article by R. W. Newcombe in "The English Electric Journal", March 1956, noted in bibliography.)*

would operate whereas for faults on the secondary side, when the fault current in the primary is reduced due to transformer impedance, the inverse element would be operative as dictated by the time grading.

Fig. 15-10 will serve to illustrate the application of I.D.M.T. relays combined with high set instantaneous relays.

The inverse definite minimum time relay noted assumes a characteristic time/current curve to B.S. 142 but in passing it may be noted that relays having what are described as "very inverse D.M.T." and "extremely inverse D.M.T." are available. These relays have been developed by The English Electric Co. Ltd. to cover (a) those cases where there is a substantial reduction of fault current as the distance from the power source increases and (b) for the protection of feeders where peak switching-in currents are experienced so that the relay has a long time-characteristic at peak current values. The "extremely inverse" relay also finds application where discrimination with quick-acting fuses is necessary. The characteristics of these special relays and examples of their application have been noted in some detail in an article by Newcombe (see bibliography).

Up to this stage, the abnormal conditions against which protection has been sought have been those involving two or three phases of a three phase system, i.e. conditions (a) and (c) of our original summary. At least initially, however, most fault conditions arise due to an insulation failure on one phase allowing current to flow to earth, a condition which may lead rapidly

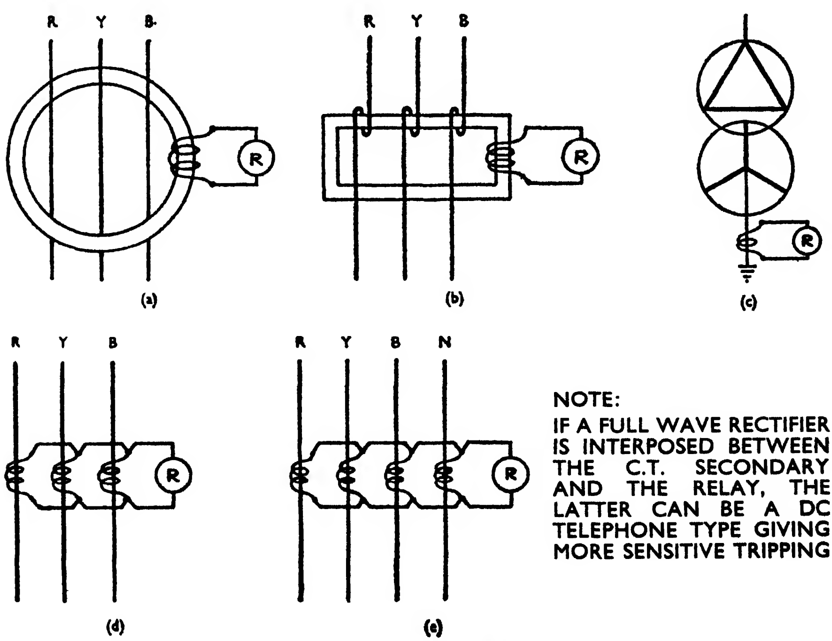


FIG. 15-11.—*Basic forms of earth-fault protection.*

to a fault between phases and, in passing, of danger to personnel. It is therefore desirable to consider some form of protection which will detect a fault to earth and disconnect it from the system in the shortest possible time.

In a limited number of switchgear types in the medium-voltage range, this form of protection can be achieved by a single direct-acting trip coil but, as in the case of an overload coil, it is unsuitable where discrimination is necessary and generally it is not too sensitive. Greater sensitivity can be obtained by using a moving-coil relay operated from a full wave a.c./d.c. rectifier but for discrimination and sensitivity a relay of the I.D.M.T. type offers the best solution.

The single trip coil or relay employed for earth leakage or earth-fault protection will be connected in the secondary circuit(s) of one or more current transformers as shown in Fig. 15-11. In this illustration, (a) and (b) represent two forms of core-balance current transformer, that at (a) with the three primary conductors passing through a simple ring core without break while at (b) the core has three primary windings to which the primary conductors are connected. At (c) is shown how a single current transformer may be inserted in the neutral earth connection of a generator or transformer, a scheme which, when applied to a transformer, can be arranged to trip out the circuit-breakers on both the primary and secondary sides. At (d) and (e) schemes are shown using three or four individual current transformers on three-wire or four-wire circuits respectively. In each of these except that at (c) the principle of operation is based on the fact that in a balanced circuit, currents in the three lines sum up to zero as shown vectorially in Fig. 15-12. When a fault between one line and earth occurs, this balance

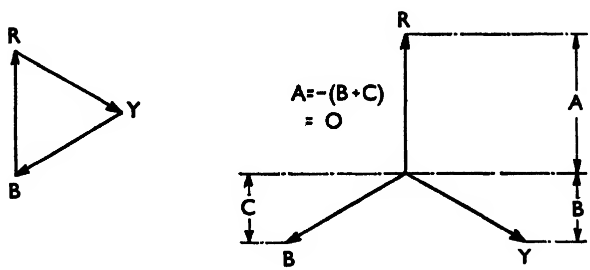


FIG. 15-12.—*Showing how currents in a healthy balanced three phase circuit, sum up to zero.*

is upset and the out-of-balance, or residual current, is fed to the relay and if this current is equal to the relay setting operation occurs to cause disconnection of an associated circuit-breaker.

A balanced circuit as in Fig. 15-12 does not necessarily require that each current vector R.Y.B. must be equal in magnitude or phase. With loads which are unbalanced, the current in each line may indeed be unequal but, so long as the system is healthy, i.e. no earth-fault or leakage exists, the three vectors representing these currents will still form a closed triangle

and the protective gear will not function. Only when current from one line flows via earth and the earthed neutral point of the system is the balance upset and the three vectors will then not form a closed triangle.

This theory, outlined in simple language, is related to symmetrical components as discussed in Chapter IV involving zero phase sequence current. It is important to note that these forms of protective gear do *not* give protection against so-called "single phasing", i.e. an open circuit on one line. Note also that technically there is a difference between (a) (b) and (d) (e) in Fig. 15-11 in that with (a) and (b) it is the fluxes in the core which are normally balanced whereas in (d) and (e) the balance is between the three or four secondary currents.

Applied to an open-ended radial feeder this type of protection functions to isolate that circuit and no other when a fault occurs on the feeder. If applied to an incoming feeder it will function to disconnect that feeder and the supply to the switchboard will be lost, even though the fault is on outgoing feeders. This is true also if applied to a generator or transformer

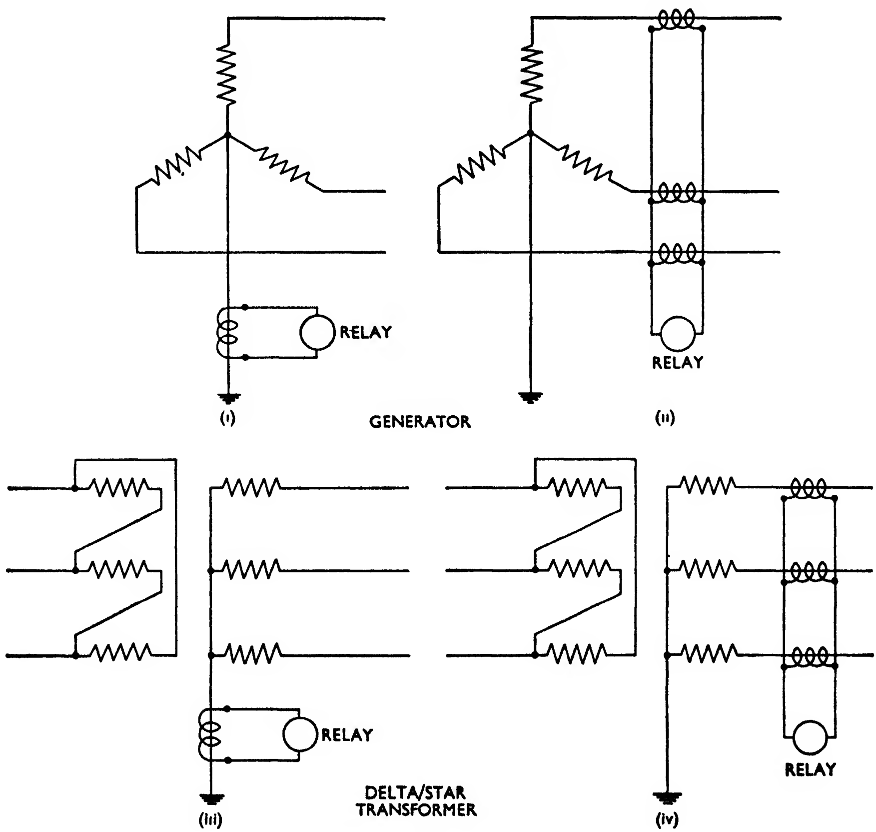
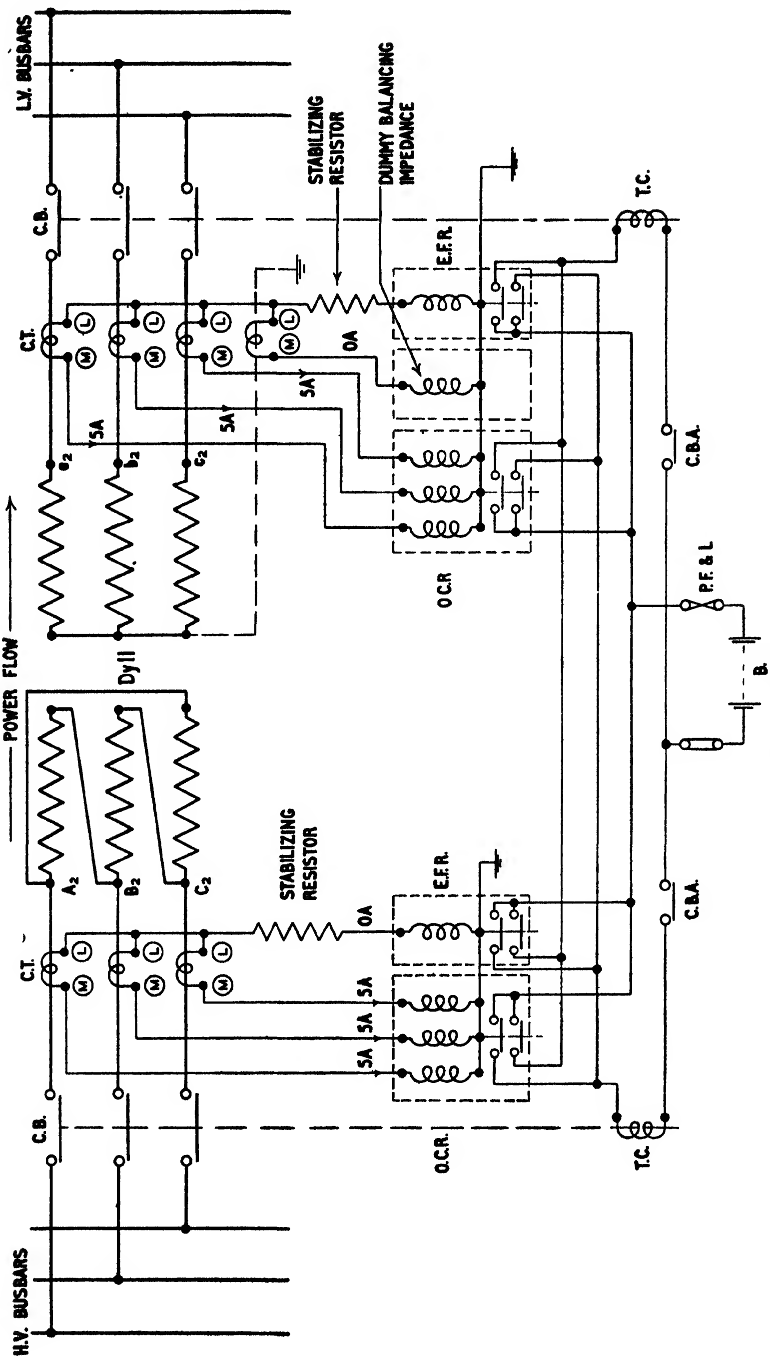


FIG. 15-13.—*Unrestricted earth-fault protection.*



C.B. CIRCUIT-BREAKER C.T. PROTECTIVE CURRENT TRANSFORMER C.B.A. CIRCUIT-BREAKER AUXILIARY SWITCH
T.C. TRIP COIL O.C.R. OVERCURRENT RELAY E.F.R. EARTH FAULT RELAY
P.F. & L. PROTECTIVE FUSE AND LINK B. BATTERY

FIG. 15-14.—*Overcurrent and earth-fault protection of a three phase delta/star connected transformer.*

circuits, as in Fig. 15-13, in any of the forms shown. In all these cases the earth-fault may occur at points well beyond the immediate circuit to which the protection is applied but because the protective gear cannot discriminate, the circuit-breaker controlling the source of supply will be opened unnecessarily.

It follows from what has been said that earth-fault protection should be applied to individual outgoing feeder circuits and not to an incoming feeder which gives supply to a group of circuits and, if it is applied to a generator or transformer circuit, it should be of the type known as "restricted" earth-fault protection.

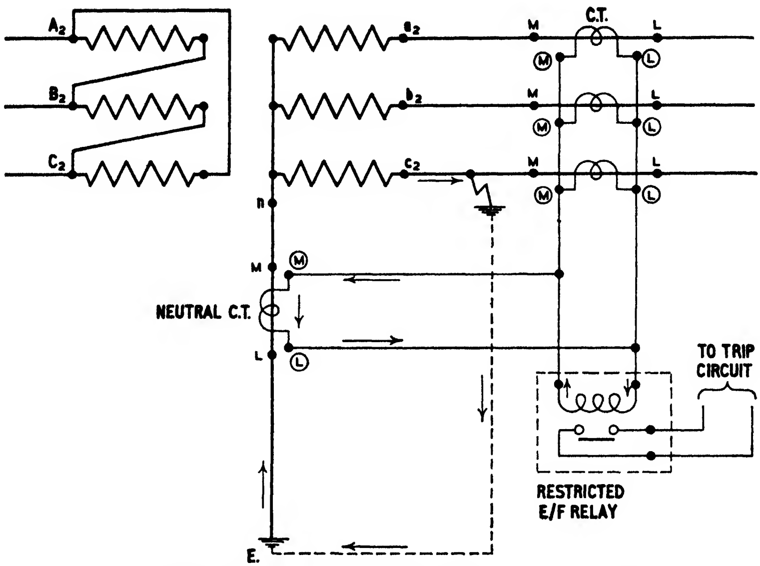
Fig. 15-14 shows how overcurrent and earth-fault protection may be applied to the primary and secondary sides of a three phase delta/star power transformer.

On the primary (delta) side, the use of three current transformers, connected as shown to the earth-fault relay, give restricted protection, i.e. to the delta winding only as this is unearthed. On the secondary side, however, we must add a fourth current transformer in the neutral connection to earth if we wish to restrict the earth-fault protection here to the secondary windings and connections thereto. This fourth current transformer is connected in parallel with the three line current transformers and the protective system will now discriminate between faults *external* to the protected zone and those *within* the zone, operating only for the latter as indicated in Fig. 15-15.

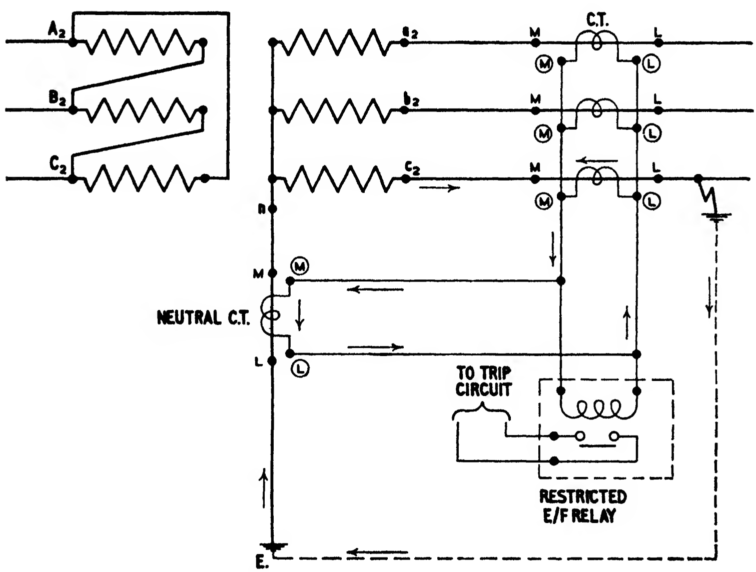
For the sake of simplicity, the secondary current in the upper diagram is shown to be wholly circulating through the relay. In fact, a part of this current divides to pass through the secondary windings of the three line current transformers which are in parallel with the one in the neutral connection. The exact division will depend on the relative impedances of the relay coil and the secondary windings but it must be remembered that this division of current will have an effect on the relay settings. Kaufmann (see bibliography) deals with this problem at some length in his book.

It will be noted in Fig. 15-14 that (a) a dummy balancing impedance has been connected in series with the neutral current transformer on the secondary side of the power transformer and (b) a stabilising resistor has been connected in series with the earth-fault relay. The purpose of (a) is to balance the line and neutral current transformers when an *external* fault occurs and the dummy impedance must be equal to that of one of the overcurrent relay elements. The stabilising resistor (b) is applied where the earth-fault relay is of low impedance such that "spill" currents may be sufficient to operate the relay in circumstances not calling for such operation.

In any form of balanced protection, stability must be maintained during a "through-fault", i.e. the passage of fault current to another (possibly remote) part of the system and demanding clearance at that other point. Unless the three current transformers are perfectly matched in ratio and other characteristics, these through currents, often of extremely high magnitude, can readily cause a "spill" current to appear at the relay and if of sufficient magnitude, cause it to operate. This is a particular hazard when a sensitive earth-fault relay is set to operate at one ampere or less as no matter how well the current transformers are designed and manufactured the primary current will not be reproduced perfectly in the secondary and



SHOWING OPERATION ON FAULT INSIDE ZONE



SHOWING NON-OPERATION ON FAULT OUTSIDE ZONE

FIG. 15-15.—*Diagrams showing principle of restricted earth-fault protection for transformers.*

a "spill" current will result. The stabilising resistor is therefore added to increase the impedance of the relay circuit and to reduce the value of spill current reaching the relays.

Many medium-voltage systems operate as four-wire and here restricted earth-fault protection for a star winding is applied in one of two ways depending on whether the neutral is earthed direct at the winding or at some point on the *load* side of the protective current transformers. Both conditions are noted in Fig. 15-16 from which it will be seen that either five or four current transformers must be employed.

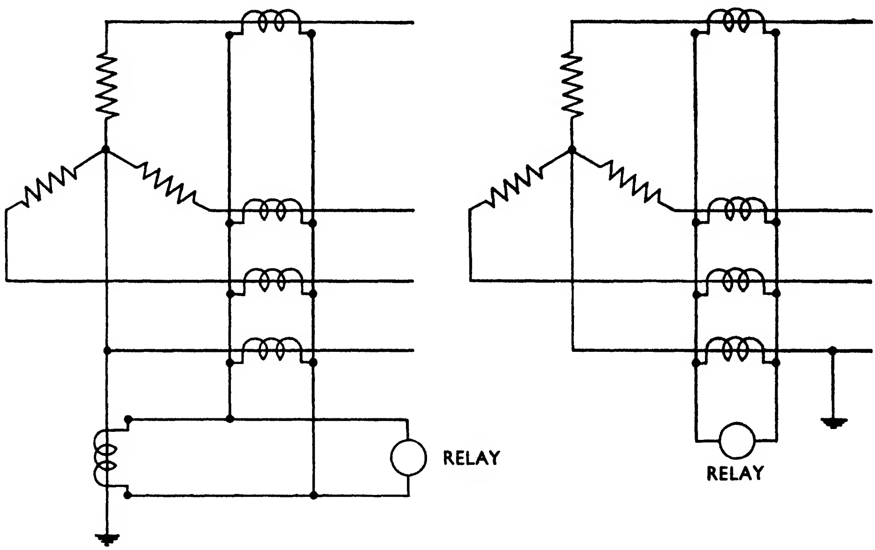


FIG. 15-16.—*Restricted earth-fault protection applied to a four-wire system using five or four current transformers.*

When both overcurrent and earth-fault protection is applied to a circuit by I.D.M.T. relays, two overcurrent and one earth-fault elements are generally combined in a single relay, connected as in Fig. 15-17. The earth-fault element will be very similar to those we have discussed for overcurrent conditions but the operating coil will be tapped to cover a range of 10% to 40% in seven equal steps. Its application on a time graded basis arranged to give discrimination with relays in series will also be as discussed for overcurrent.

Up to this point we have considered the use of I.D.M.T. relays for the protection of simple "open end" feeders and for feeders in *series*. It will, however, be clear that if applied to two or more feeders in *parallel* some other feature will be necessary to ensure that *only* the faulty feeder is disconnected. A typical system of this type is shown in Fig. 15-18 where three feeders are connected in parallel between a generating station and a remote supply point.

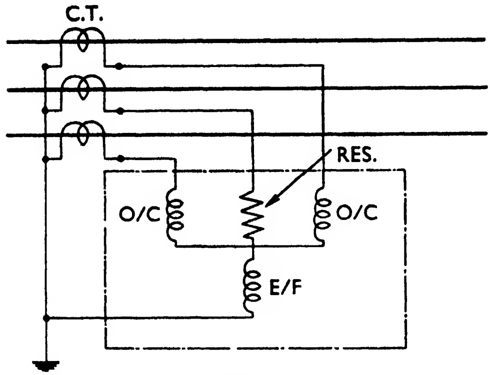


FIG. 15-17.—*Combined overcurrent and earth-fault relay.*

For such a system, the use of overcurrent and earth-fault relay protection is still valuable, but the relays used at the receiving end must be of the directional type; that is, they must operate only in one direction of feed, which is that of feeding a fault.

Referring to Fig. 15-18, let it be assumed that a fault occurs on No. 2 feeder as shown at F. It will be seen that this fault is fed via three routes, (*a*) directly along feeder No. 2 from the power source, (*b*) from feeder No. 1 via the receiving end busbars, and (*c*) from feeder No. 3 via the receiving end busbars. Thus, to clear the fault, it is necessary that the two circuit-

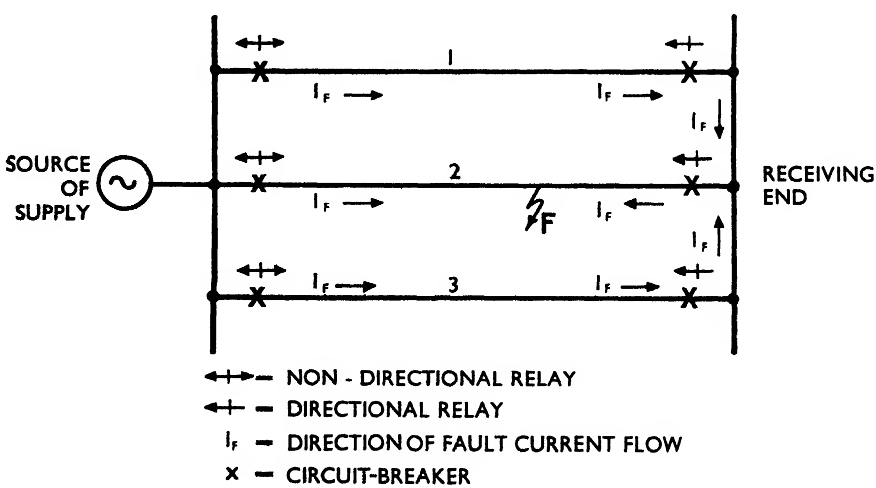


FIG. 15-18.—*Application of directional and non-directional relays to parallel feeder protection.*

breakers on No. 2 feeder (one at each end) open, while *all other* breakers remain closed. It will be noted that on the circuit-breakers at the power source end, relays of the non-directional type are used while, at the receiving end, the relays are directional, operating only when fault power is feeding in the direction of the arrow. This being so, it is clear that with a fault at F, *all three* relays at the power supply end will start to operate while, at the receiving end, *only* the relay on feeder No. 2 will start. But, we do not want the circuit-breakers on feeders Nos. 1 and 3 at the source to open, and that they remain closed is assured by reason of the fact that the fault current in these two feeders is very much lower than that in feeder No. 2—because it is divided in two parallel paths, each of greater impedance than that of the direct feed. Also, by using inverse time characteristic relays, the operating times will be long by comparison and the circuit-breakers at either end of feeder No. 2 will have isolated that feeder before relays 1 and 3 have completed their travel, thus clearing the fault and enabling these relays to reset, and feeders 1 and 3 to remain in service. The exact distribution of current under fault conditions is outside the scope of this chapter, but the problem has been discussed in Chapter IV.

When a "teed" feed is taken away from parallel feeders, the use of directional and non-directional I.D.M.T. relays can be used as shown in Fig. 15-19.

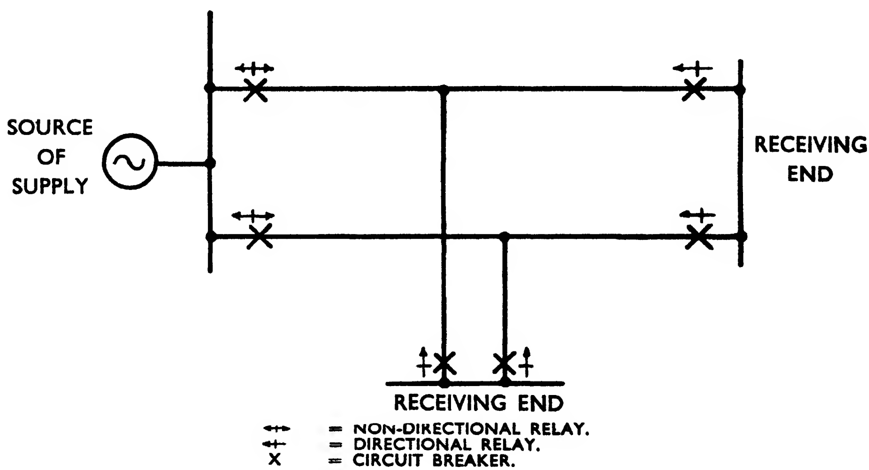


FIG. 15-19.—*Parallel feeders with tee-off feeders.*

In these examples, the non-directional type of relay is that which we have previously considered but to make it sensitive to direction, a directional element must be added and which will control the I.D.M.T. overcurrent or earth-fault element. This arrangement ensures that with current flow in one predetermined direction, the directional element will not operate and will thus render the I.D.M.T. element inoperative.

When the current flows in the opposite direction the directional element will operate and will place the I.D.M.T. element in circuit to operate according to its characteristics.

Directional I.D.M.T. relays operate on the wattmeter principle employing both current and voltage elements. Fig. 15-20 shows the typical connections (internal) of such a relay.

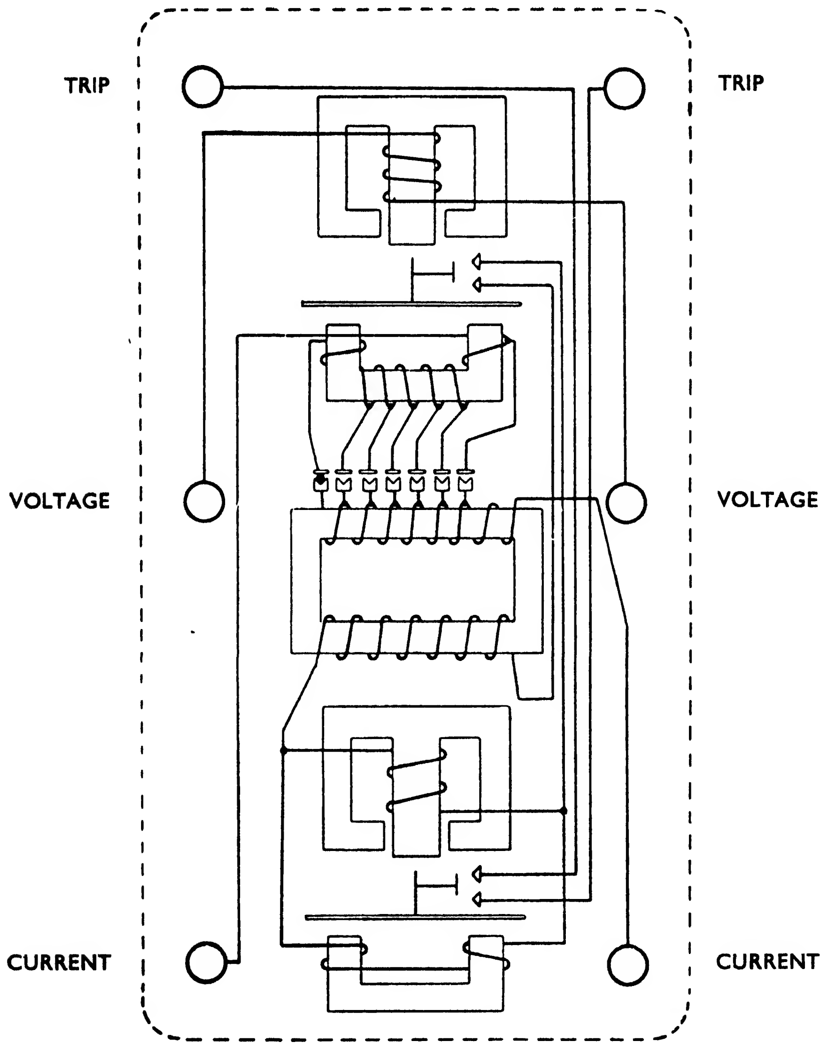


FIG. 15-20.—*Internal connections for directional I.D.M.T. relay.*

For operation of non-directional relays, only three current transformers are necessary. For directional relays, however, a voltage supply is essential, involving three phase voltage transformers (or the equivalent two single phase transformers in open delta) used as shown in Fig. 15-21. With directional earth-fault relays, however, when only one relay element is used to protect against earth-faults on any of the three phases of a three phase circuit there is the problem of ensuring that the voltage applied to the directional element voltage coil corresponds in phase to that of the current in the current coil. This voltage will be the residual voltage of the system and will be the vector sum of the three line to earth voltages.

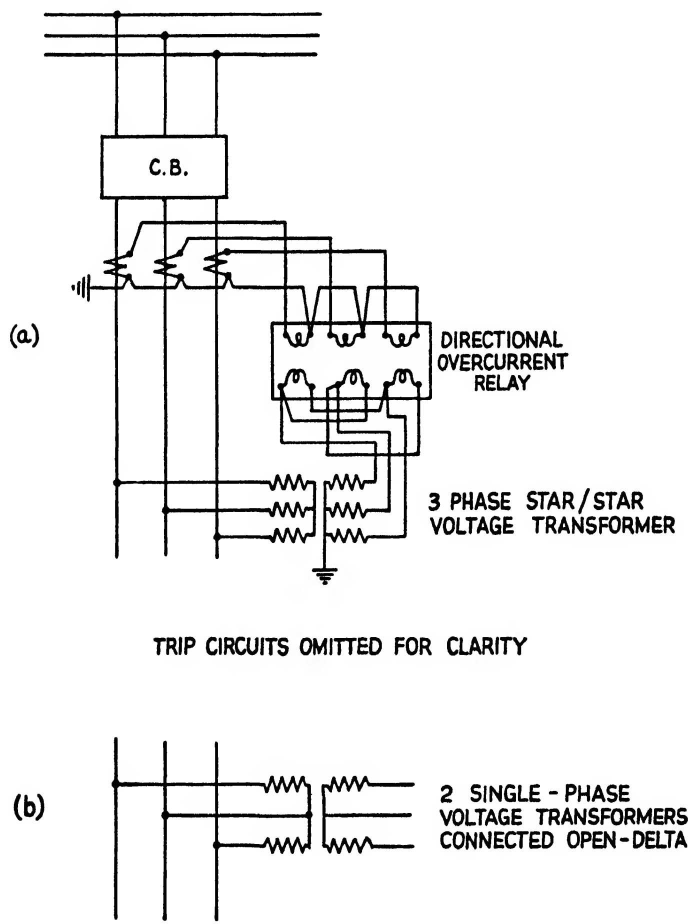


FIG. 15-21.—*Voltage transformer connections for directional overcurrent relays.*

Three methods of achieving this are shown in Fig. 15-22. In diagram (a) it will be noted that the neutral point of the high-voltage star winding is earthed. On a system where the neutral is earthed, an earth-fault on one line short-circuits the winding connected to that line. In a normal (three-limb) transformer, the resultant flux due to two healthy lines returns through the transformer limb of a faulty line, inducing a heavy short-circuit current in the winding on that limb. This induces a voltage which is reflected in the corresponding secondary winding, and the voltage across the open point of the delta will not be the true residual. In order to obviate this it is neces-

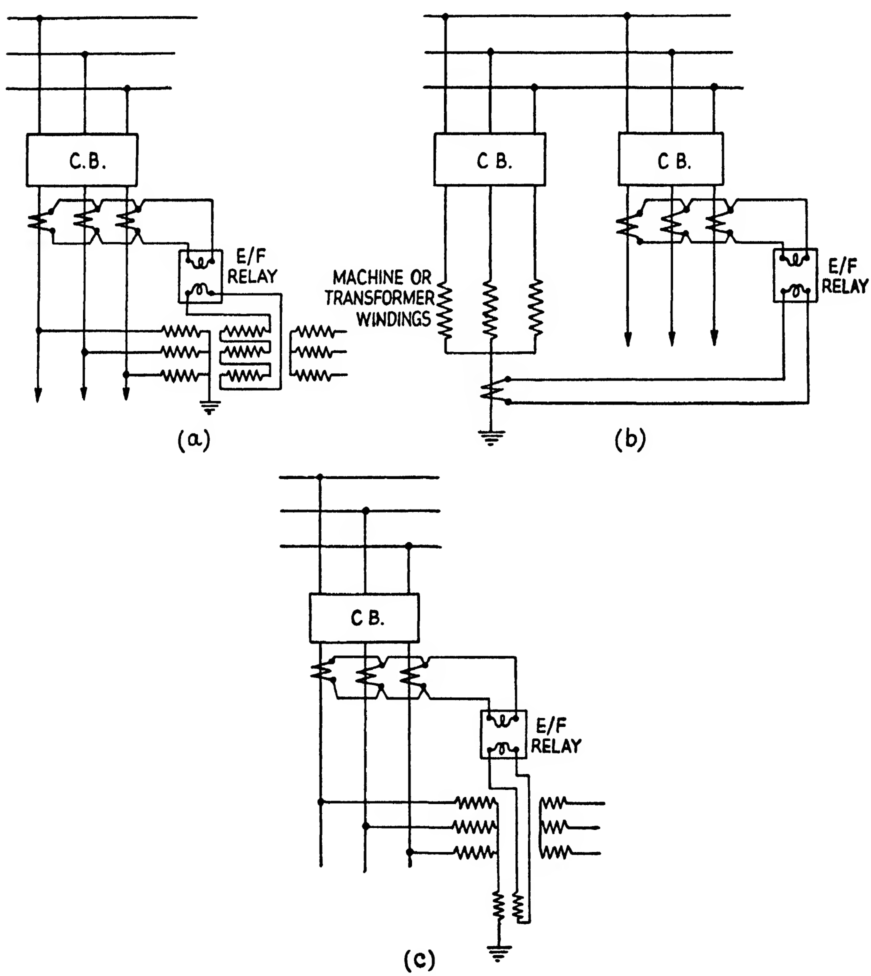


FIG. 15-22.—*Voltage connections for directional earth-fault relays.*

sary to provide a low reluctance return path of sufficient cross section to carry the maximum value of unbalanced flux without saturation. This is achieved by the use of a five-limb transformer as shown in Fig. 15-23. The use of an open delta connected tertiary winding to give a true residual voltage is demonstrated in Fig. 15-24.

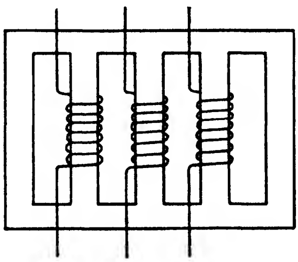


FIG 15-23 —*Elementary diagram of five-limb transformer*

It will be seen that it is necessary to consider three cases, (a) where the system is healthy, (b) where there is an earth-fault on one phase of the system and the supply neutral is not earthed, and (c) where there is a fault on one phase of the system and the supply neutral is solidly earthed

(a) Under healthy conditions all three phases will be balanced and the residual voltage of the system will be zero The three e m f's in the delta winding will form a closed triangle and the residual voltage V_R across the relay will be zero See Fig 15-24(a)

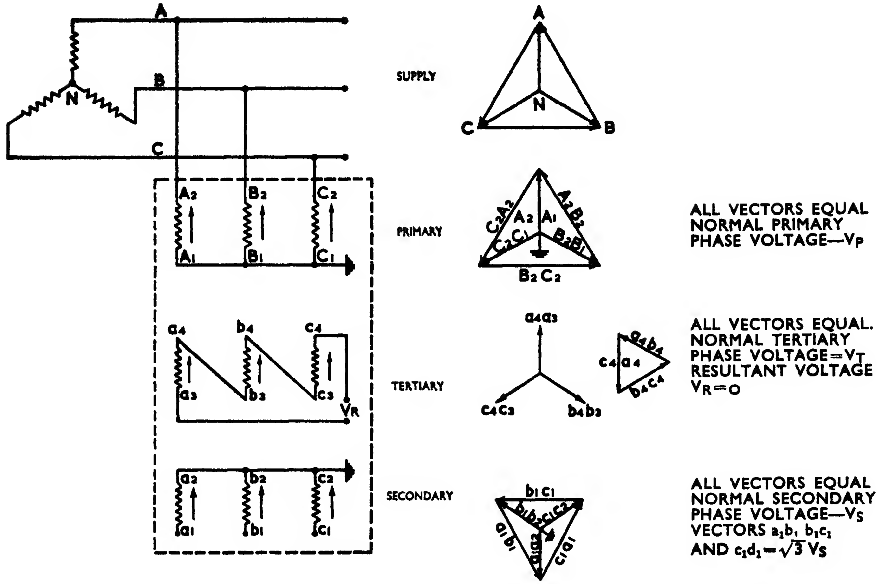
(b) If there is an earth-fault on phase C of the system when the supply neutral is unearthed, then phase C will be at earth potential and the neutral point of the supply will be at a potential equal to the normal phase voltage, as shown in Fig 15-24(b) The phase to earth voltage will now equal the normal line to line voltage, i e it will be $\sqrt{3}$ times as great as normal and the phase displacement between A2A1 and B2B1 will now be 60° instead of the normal 120° As the phase to earth voltage has increased by $\sqrt{3}$, so the flux in the core will increase by $\sqrt{3}$, as also will the induced e m f in each phase of the tertiary winding These e m f's will be displaced 180° from the primary and will sum up to give a resultant voltage—

$$V_R=\sqrt{3}\cdot\sqrt{3}\,V_T=3\,V_T$$

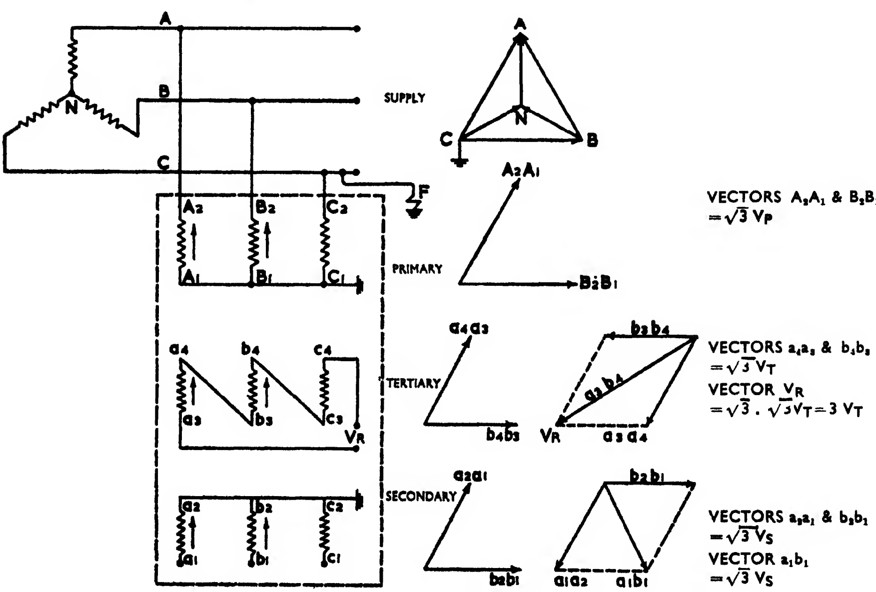
i e three times as great as the normal tertiary phase voltage

If the secondary of the voltage transformer is rated at 110 volts then the normal phase voltage will be $110/\sqrt{3}$, i e 63 5 volts and the residual voltage across the relay will be three times this value, i e 190 volts Transformers operating under these conditions are noted as category Z in B S 2046 It is also noted from the vector diagram that the resultant line to line voltage of the secondary winding will not exceed 110 volts

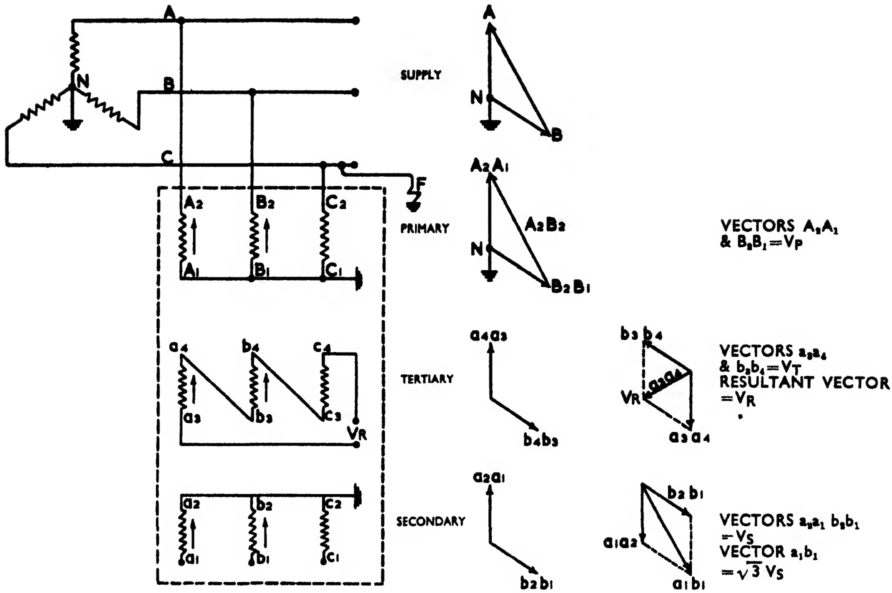
(c) If there is an earth-fault on phase C of the system and the supply neutral is solidly earthed, then (neglecting the impedance of the fault and of the supply) the voltage across phase C will disappear completely and the vector diagram appear as in Fig 15-24(c), the other phase voltages remaining at their normal values The e m f's in the tertiary winding will be displaced by 120° and will sum up to give a residual voltage V_R equal in magnitude



(a) HEALTHY SYSTEM



(b) EARTH FAULT ON PHASE C
SUPPLY NEUTRAL UNEARTHED



(c) EARTH FAULT ON PHASE C
SUPPLY NEUTRAL SOLIDLY EARTHED

FIG. 15-24 (*above and opposite*) *Principle of the residual voltage transformer.*

to the normal phase voltage V_T, i.e. $V_R = 63\cdot5$ volts. Transformers operating under these conditions are noted as category X in B.S. 2046. It will also be seen that the resultant voltage across the secondary winding will not exceed 110 volts.

Cases (b) and (c) represent two extreme conditions i.e. where the system is either unearthed or is earthed solidly. If now the neutral is earthed through a resistance or impedance, the residual voltage across the tertiary winding will be a value somewhere between 63·5 and 110 volts, dependent on the value of resistance or impedance in the neutral. Residual voltage transformers operating under these conditions are noted as category Y in B.S. 2046.

Directional overcurrent and earth-fault protection as described for parallel feeders is also a popular form of protection for ring main circuits, a simple form of which is shown in Fig. 15-25. Here a single source of supply feeds a ring cable which is interrupted in its course at four transformer substations. At the power source, two circuit-breakers control the ring main, each being fitted with non-directional relays.

At each substation the ring is broken by the insertion of two circuit-breakers and these are fitted with directional relays such that operation occurs only when fault current of appropriate magnitude flows *away* from

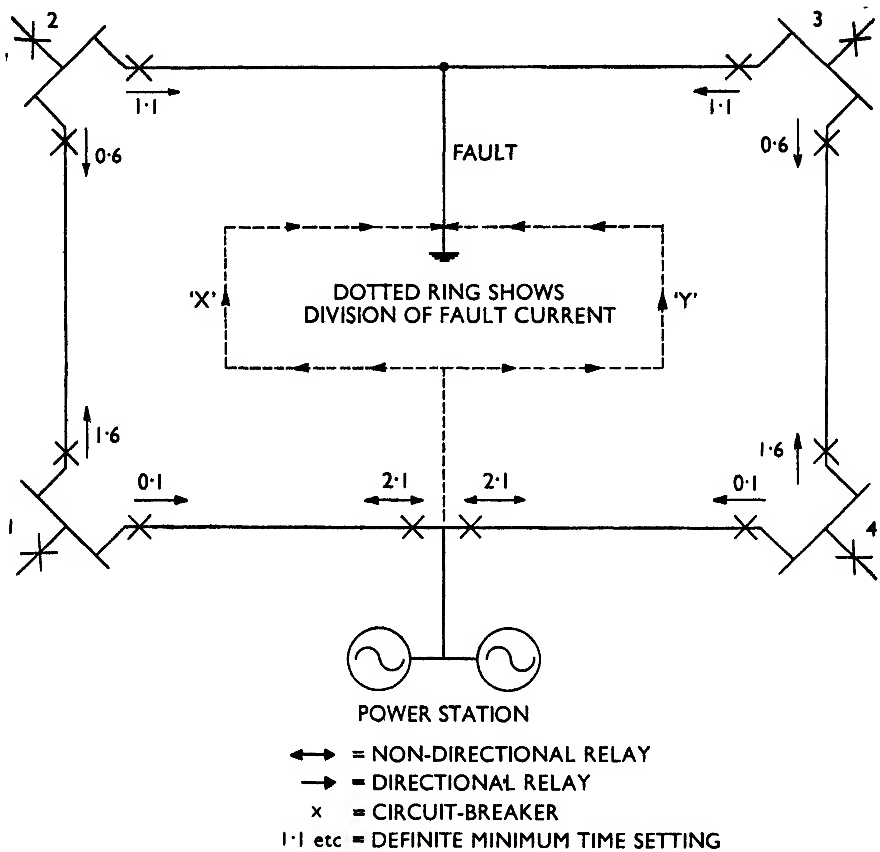


FIG. 15-25.—*Directional protection applied to a simple ring main.*

the substation, as indicated by the arrows. Thus, if a fault occurs on the cable between substations 2 and 3, only the circuit-breakers at each end of this cable will open, leaving *all* substations in service but isolating the faulty cable. At each relay a figure, e.g. 1·1, is given. This is the selected definite minimum time setting of the relay and it will be noted that, starting at the source of supply in either direction, the *outgoing* relay settings are progressively reduced. This principle is shown in Fig. 15-26 where the ring is developed into two radial feeders (a) and (b) and superimposed at (c), which is the ring main developed into a straight line.

Assuming a fault at "F" (Fig. 15-25) between substations 2 and 3, fault power is fed via two paths "X" and "Y", dividing in inverse ratio to their impedances. The fault power feeds through every substation but at each of these one set of relays will be inoperative because the power flow is against the arrow, while the other set will be operative because the power flow is with the arrow.

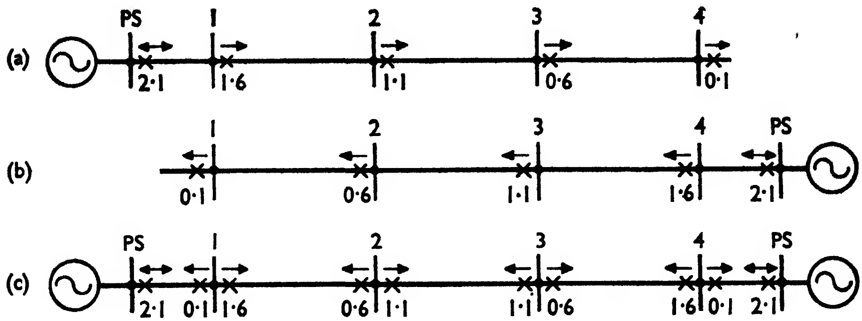


FIG. 15-26.—*Development of ring main scheme.*

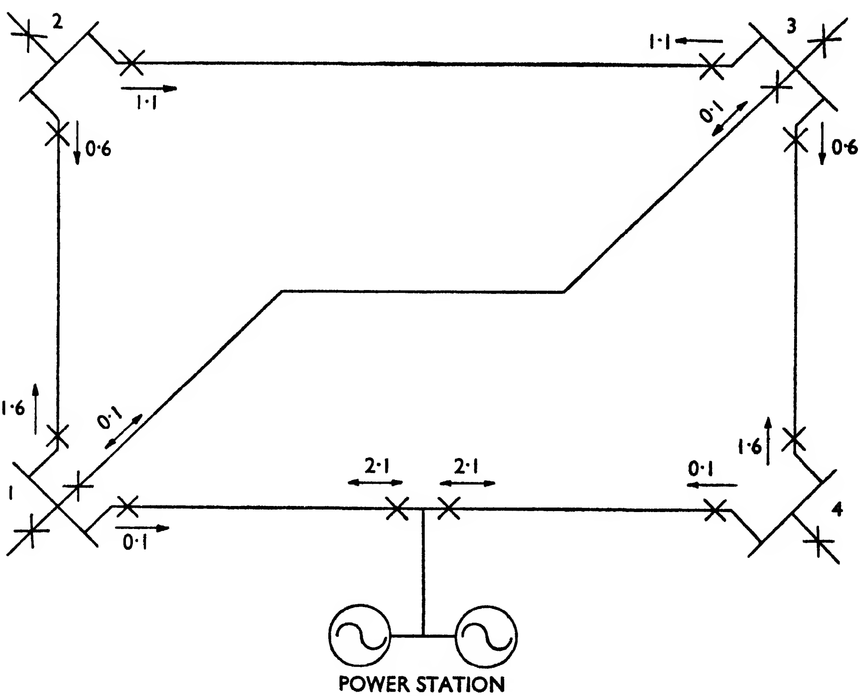


Fig. 15-27.—*Directional protection applied to a ring main with interconnector.*

Considering the fault power flow in the direction "X" first, the relays at the power source and on the outgoing side of substations 1 and 2 have definite minimum time settings of 2·1, 1·6 and 1·1 seconds respectively. The 1·1 second relay on the outgoing side of substation 2 will obviously be the first to complete its operation, trip out the associated circuit-breaker and thus clear the fault feed in this direction, the relays at the power source and substation 1 immediately resetting.

Considering now the feed in the direction "Y", the relays at the power source and on the outgoing sides of substations 4 and 3 have definite minimum time settings of 2·1, 1·6 and 1·1 seconds respectively, thus ensuring that the circuit-breaker on the outgoing side of substation 3 with its 1·1 second setting will clear the fault leaving the remaining relays to reset.

In some circumstances, a ring main of the type shown in Fig. 15-25 may have the additional feature of an interconnector between two selected substations as shown in Fig. 15-27. The arrangement of relays around the ring is as previously noted but on the interconnector, relays of the non-directional type are used, and with a low definite minimum time setting.

Reverting to Fig. 15-25, we note that if a fault occurs on the cable between the power source and substation 1, the circuit-breaker at the power station has a definite minimum time setting of 2·1 seconds. The fault on this section would be isolated at the substation by the 0·1 second relay but would continue to be fed from the power station for another two seconds. Here then is an ideal situation for applying the high set instantaneous element as discussed on page 451, in order to remove the fault as rapidly as possible.

It has been shown in Figs. 15-14 and 15-15 how earth-fault protection can be applied to a star winding (of a generator or transformer) in such a way as to limit the protection afforded to a defined zone. Zonal protection is an important feature of the well-known Merz-Price circulating current system, a differential scheme which can be applied to protect generators, transformers and feeders against phase to phase or earth-faults.

The system is discriminating in that it disconnects only the apparatus or feeder which is faulty and it should be stable for any faults beyond the protection zone, i.e. through-faults.

When applied to a generator, the scheme is very simple. The fundamental principle is that, under healthy conditions, the current entering at one end of a machine winding is identical, both in phase and magnitude, with that leaving the winding at the other end. On the occurrence of an internal fault this equality is disturbed and, when the unbalance reaches the necessary value of relay operating current, the plant is disconnected from the system by opening the main circuit-breaker.

In Fig. 15-28 is an explanatory diagram showing the principle of the circulating current system. It will be noted that current transformers (which have similar characteristics and ratio) are connected on both sides of the machine winding and a relay winding is connected across the pilot wires between the two current transformers. Under healthy conditions, the current distribution is as shown at (a), no current flowing in the relay winding. Should a fault occur, either to earth, as shown at (b), or between phases, the conditions of balance are upset and current flows in the relay winding to cause operation. It will be noted that at (b) the fault is shown at a point

between the two current transformers (the location of these determine the extent of the protected zone). If the fault had occurred beyond, say, the right-hand current transformer, then operation would *not* occur as the fault current would then flow through *both* current transformers thus maintaining the balance, as shown at (a). In order that the symmetry of the burden on the current transformers shall not be upset and thus cause an out-of-balance current to pass through the relay, causing operation when not intended, it is essential that the relay be connected to the pilot wires at points of equipotential. This is illustrated at (c) in Fig. 15-28, such equipotential points being those as "a" and "b", "a¹" and "b¹" etc. In practice it is

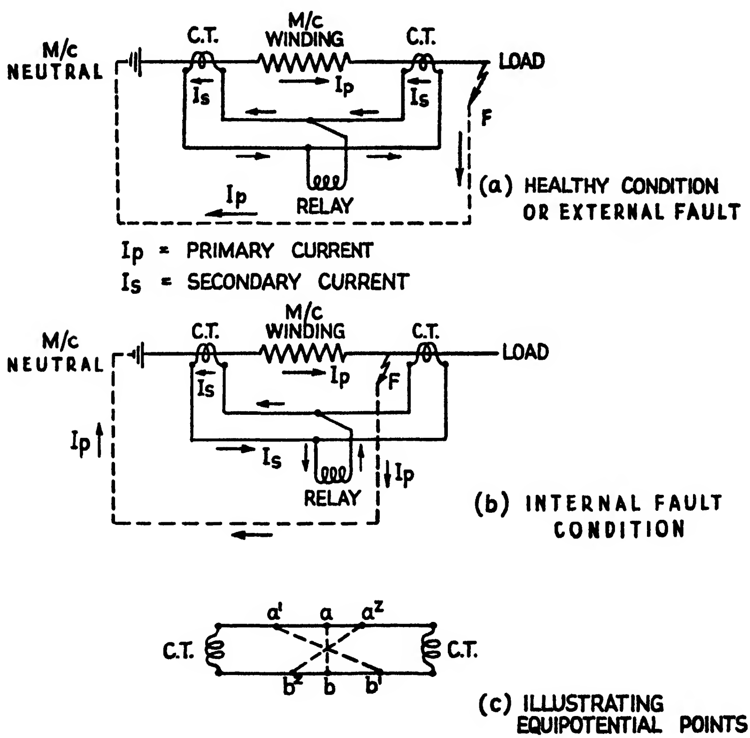


FIG. 15-28.—*Explanatory diagram to illustrate principle of circulating current protection.*

rarely possible to connect the relay to the actual physical mid-point in the run of the pilots and it is usual to make the connection to convenient points at the switchgear and to insert balancing resistances in the shorter length of pilot wire (see Fig. 15-32 for example). The resistances should be adjustable so that accurate balance can be obtained when testing before commissioning the plant.

Fig. 15-29 shows the protective gear connections for a three phase machine. It will be noted here that there are two sets of three current transformers, one set being mounted in the neutral connections (usually in the alternator pit), and the other being mounted in the switchgear equipment. Thus, not only are the machine windings within the protected zone but also the external connections to the switchgear.

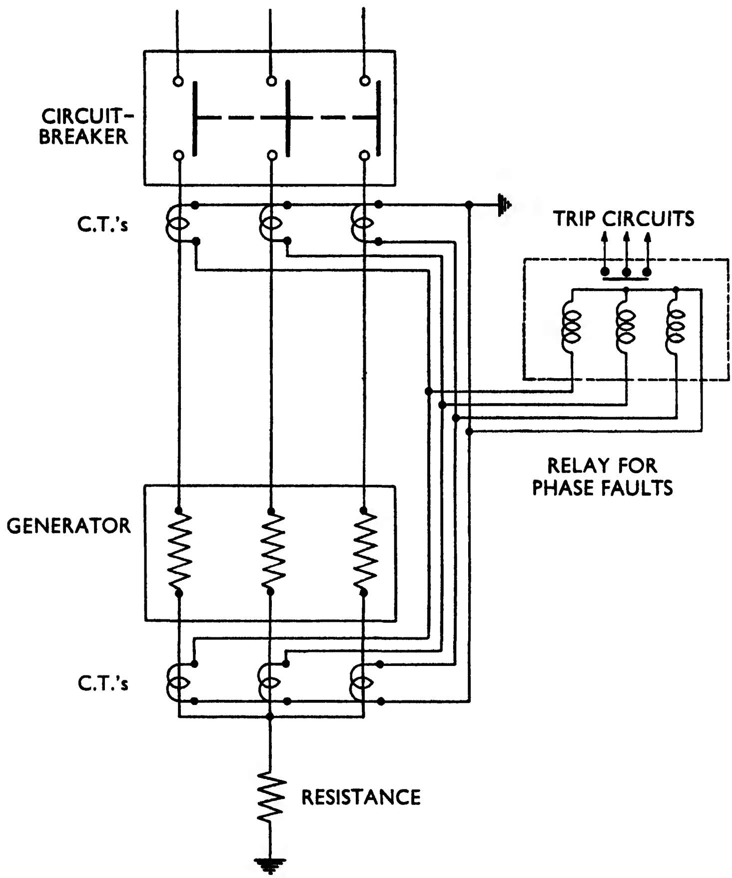


FIG. 15-29.—*Merz-Price system of circulating current protection applied to a generator.*

The two sets of current transformers are connected in star and a four core pilot cable joins the two sets. The relay coils are also connected in star, the star point being connected to the star point of the current transformers.

The relay is usually of the electromagnetic type and is arranged for instantaneous tripping. The current transformers, while being ordinary

commercial types, are selected for equality of characteristics in order that unwanted tripping may be avoided due to the spill currents which would occur if the characteristics of any opposing pair were radically different.

In order to provide for the detection of earth-faults, the modified system shown in Fig. 15-30 has been developed, use being made of an earth-fault relay element operating on the residual principle.

A complete diagram of connections for the protection of a three phase generator is given in Fig. 15-31. In addition to showing the circulating current protection so far discussed, this diagram shows the field suppression equipment and also phase-unbalance protection, some details on which will be noted later.

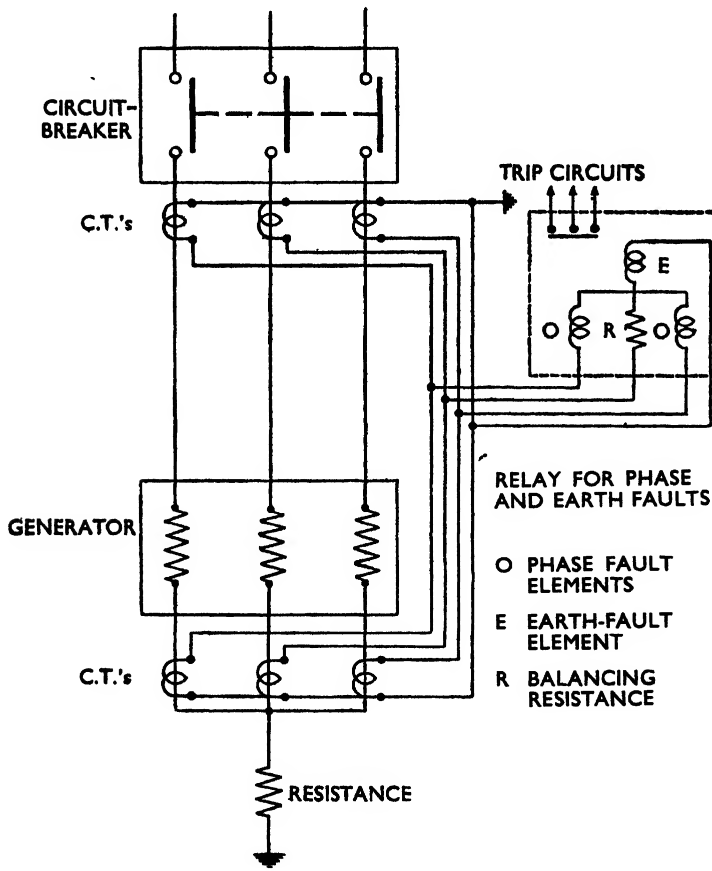


FIG. 15-30.—*Modified scheme as Fig. 15-29 to include earth-fault protection.*

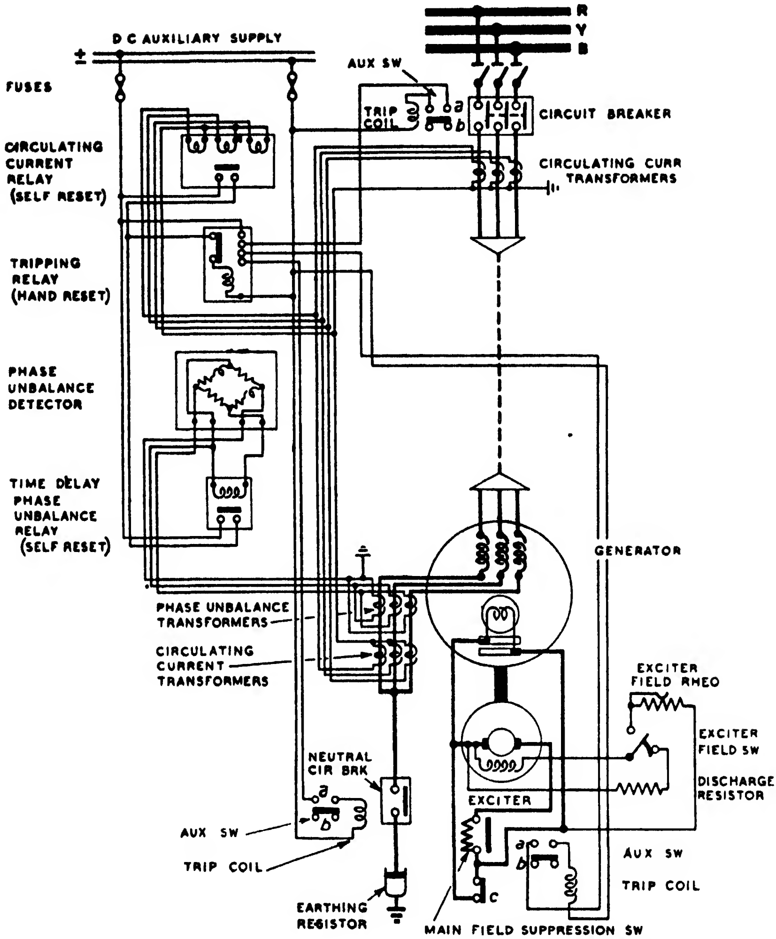
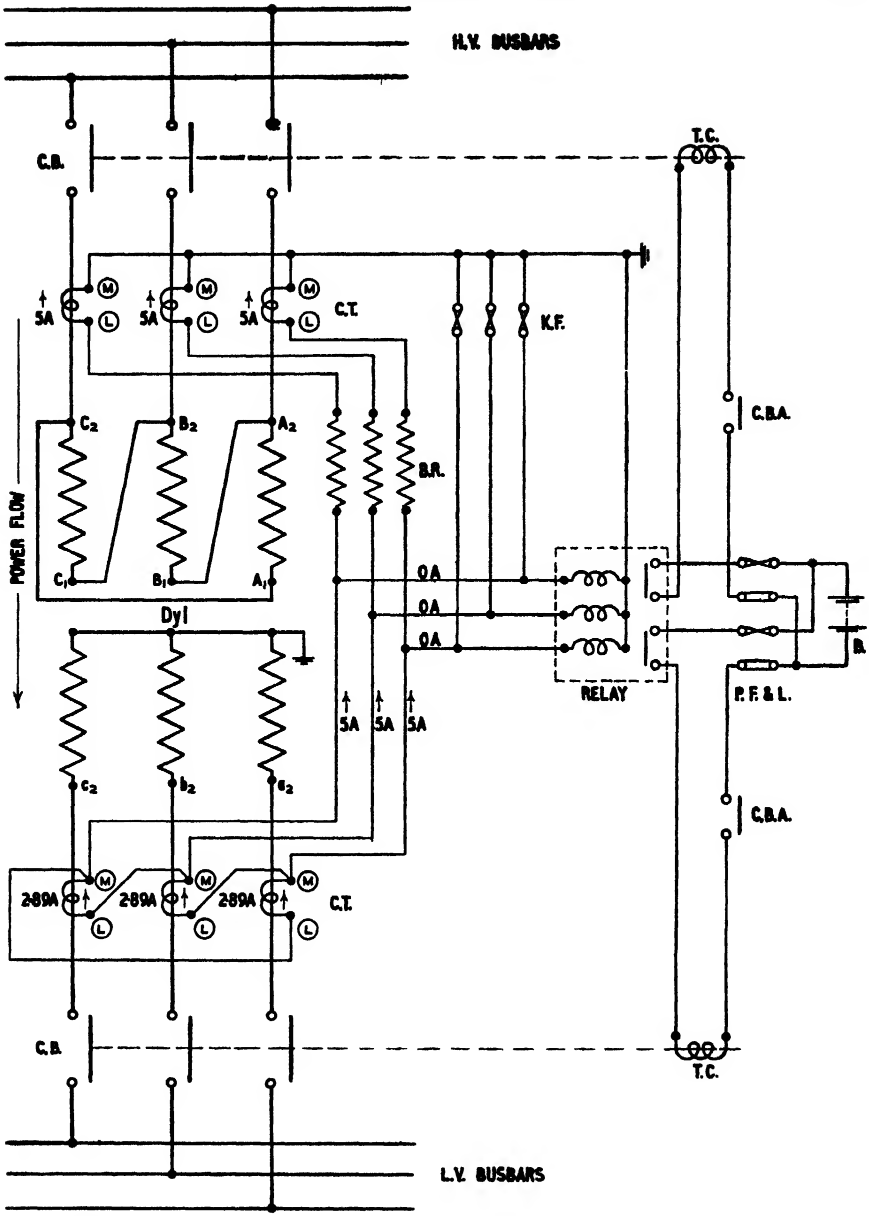


FIG. 15-31.—*Typical diagram of connections of circulating current protection with phase-unbalance protection and automatic field suppression for three phase generator having three neutral connections (Associated Electrical Industries Ltd.).*

When Merz-Price protection is applied to a power transformer, some complications arise because a phase shift may be introduced which can vary with different primary/secondary connections and there will be a magnitude difference between the load current entering the primary and that leaving the secondary.

Correction for a phase shift is made by connecting the current transformers on one side of the power transformer in such a way that the resultant currents fed into the pilot cables are displaced in phase from the individual



C.B.	CIRCUIT-BREAKER	C.B.A.	CIRCUIT-BREAKER AUXILIARY SWITCH
C.T.	PROTECTIVE CURRENT TRANSFORMER	P.F. & L.	PROTECTIVE FUSE AND LINK
T.C.	TRIP COIL	K.F.	KICK FUSE
B.R.	BALANCING RESISTOR	B.	BATTERY

FIG. 15-32.—*Merz-Price circulating current protection for a three phase delta/star connected transformer.*

phase currents by an angle equal to the phase shift between the primary and secondary currents of the power transformer. This phase displacement of the current transformer secondary currents must also be in the same direction as that between the primary and secondary main currents.

The most familiar form of power transformer connection is that of delta/star and Fig. 15-32 shows how circulating current protection is applied to such a transformer, the phase shift between the primary and secondary sides being 30 degrees. This is compensated for by connecting the current transformers associated with the delta winding in star and those associated with the star winding in delta.

In order that the secondary currents from the two groups of current transformers may have the same magnitude, the secondary ratings must differ, those of the star connected current transformers being 5 amperes and those of the delta connected group being 2·89 amperes, i.e. $5/\sqrt{3}$.

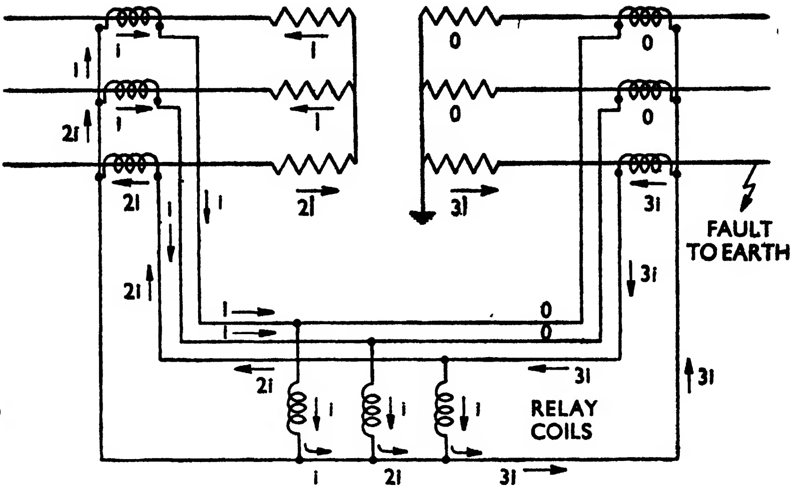
If the power transformer is connected delta/delta, there is no phase shift between primary and secondary line currents and protection is applied as for a generator but with correction for the differences in magnitude. Similarly, there is no phase shift in the case of star/star connected power transformers but here, phase correction is applied at *both* sets of current transformers, the reason being that only by this means can the protective system be stable under external earth-fault conditions. Thus, both sets of current transformers will be delta connected so that the secondary currents in the pilots from each set will be displaced in phase by 30 degrees from the line currents but both will coincide, a necessary requirement of circulating current protection. It is obvious that similarity in phase could be achieved if both sets of current transformers are connected in star but it can be shown that in this case, the protective system would be stable on through-faults between phases but *not* for earth-faults. This is demonstrated numerically in Fig. 15-33, noting that at (a) the secondary currents entering and leaving the pilots are not the same at both ends and therefore do not sum up to zero at the relays, whereas at (b) the reverse is true and no current appears in the relay coils.

As is well known, the switching in of a power transformer causes a transient surge of magnetizing current to flow in the primary winding, a current which has no balancing counterpart in the secondary circuit. Because of this a "spill" current will appear in the relay windings for the duration of the surge and if of sufficient magnitude lead to isolation of the circuit. This unwanted condition can be overcome by either connecting time limit fuses in shunt across each relay element, as in Fig. 15-32, or by arranging that the protective relay is provided with a suitable time delay.

When circulating current protection is applied to a power transformer, the relay is arranged to cause the circuit-breaker on *both* sides of the transformer to open, thus clearing the transformer completely under fault conditions.

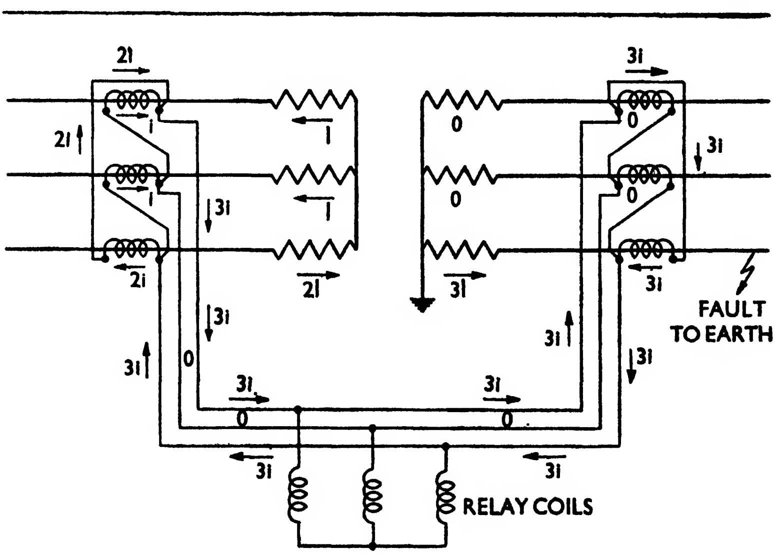
So far no mention has been made of the problem which arises when a power transformer is provided with facilities for tap changing. It has been noted that for stability under healthy or through-fault conditions, identical outputs from each group of current transformers are an essential feature of circulating current protection. It is clearly impossible for the current transformers to be matched at all tap positions unless these (the c.t's) are

(a)



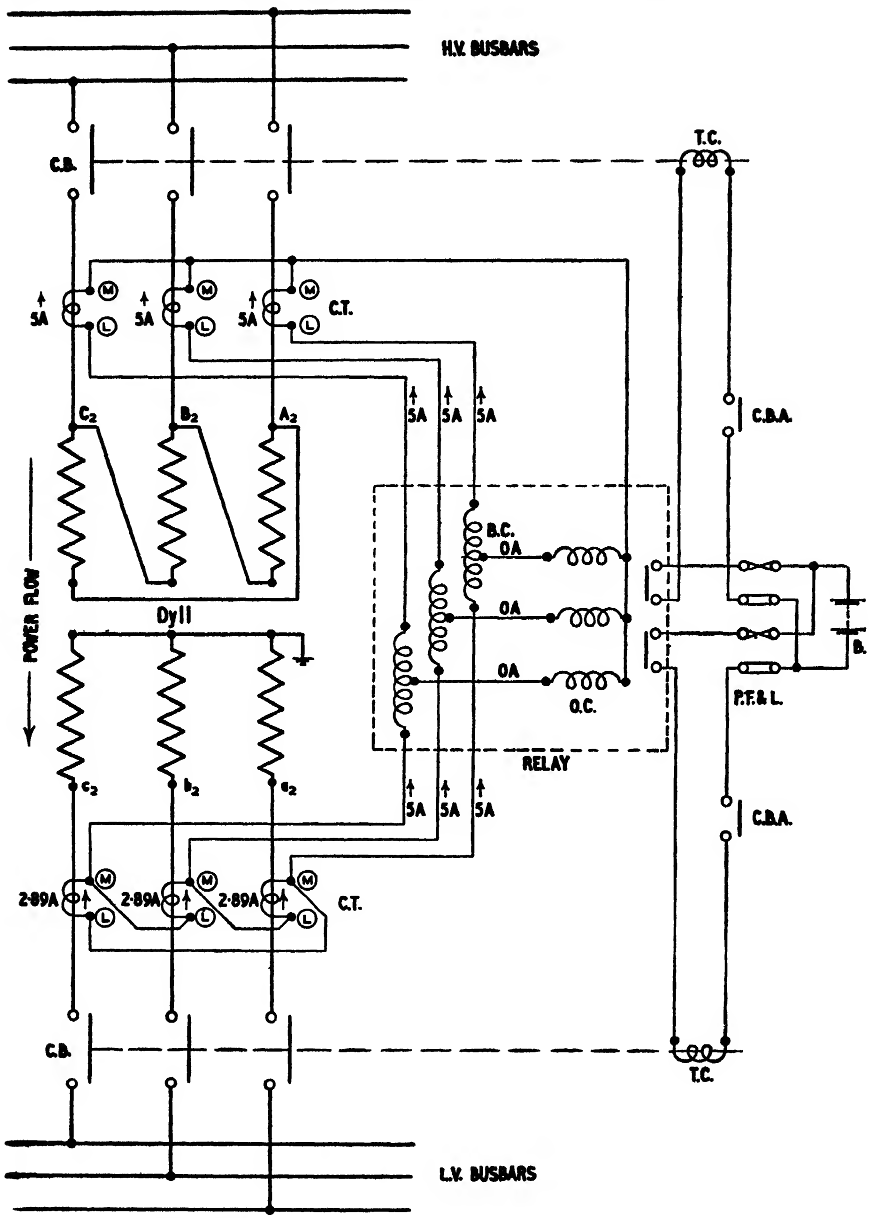
SHOWING OPERATION WHEN PROTECTIVE C.T's ARE CONNECTED IN STAR AND AN EARTH-FAULT OCCURS EXTERNAL TO THE POWER TRANSFORMER, THE RATIO OF WHICH IS ASSUMED TO BE UNITY.

(b)



SHOWING STABILITY WHEN PROTECTIVE C.T's ARE CONNECTED IN DELTA AND AN EARTH-FAULT OCCURS EXTERNAL TO THE POWER TRANSFORMER.

FIG. 15-33.—*Showing stable and unstable conditions on through earth-faults, with circulating current protection applied to a star/star transformer, due to methods of connecting current transformers.*



C.B.	CIRCUIT-BREAKER	B.C.	BIAS COIL
C.T.	PROTECTIVE CURRENT TRANSFORMER	O.C.	OPERATING COIL
T.C.	TRIP COIL	P.F. & L.	PROTECTIVE FUSE AND LINK
C.B.A.	CIRCUIT-BREAKER AUXILIARY SWITCH	B.	BATTERY

FIG. 15-34.—*Biased differential protection applied to a delta/star connected three phase transformer.*

also correspondingly tapped. This solution is generally impracticable if only because of the nature of the task of changing current transformer tappings each time a tap change is made on the power transformer. The latter function is often automatic so that it would then be necessary to make the tap changes on the current transformers automatic and simultaneous. Because of this and the normal inequalities which occur as between current transformers, many schemes for the protection of transformers have been devised in which steps have been taken to eliminate the difficulties and some of these schemes will be noted later. Here we can note that tap-changing and current transformer inequalities can be largely avoided by using a circulating current scheme which employs a biased differential relay, indicated typically in Fig. 15-34.

In each pole of this relay, there are, in addition to the operating coil, two bias or restraining windings. Under through-fault conditions, when operation is *not* required, no current should flow through the operating coil but, because of imperfect matching of the current transformers, and the effects due to tap changing, some spill current may flow in the operating coil. This, however, will not cause operation unless the ratio of operating to bias current for which the relay is set is exceeded and the restraint or bias which is applied automatically increases as the through-fault current increases, thus enabling sensitive settings to be obtained with a high degree of stability.

It may be noted in passing that the biased differential relay can be applied in generator circulating current schemes and in one such scheme the

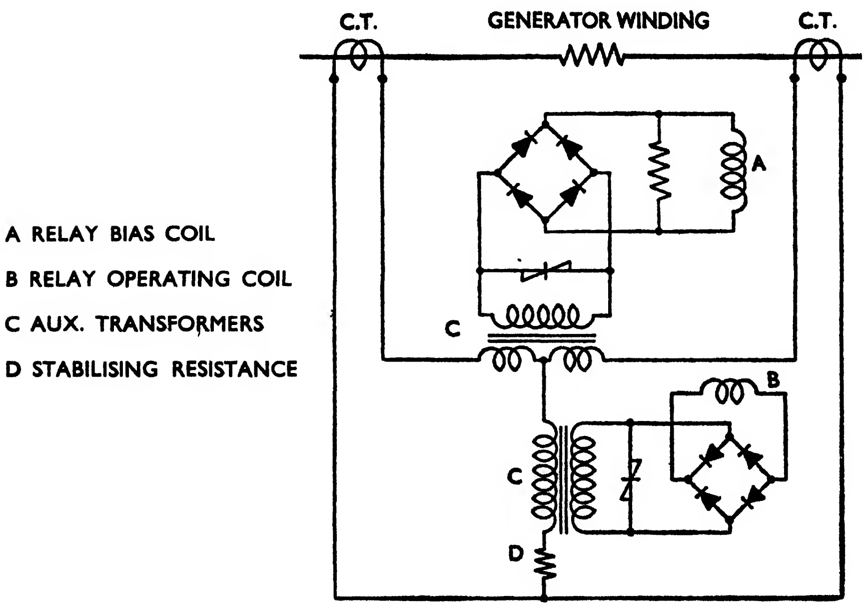


FIG. 15-35.—*Single phase diagram showing biased relay applied to generator protection (Associated Electrical Industries Ltd.).*

relay comprises a permanent magnet with a moving coil energised through metal rectifiers which convert a.c. into d.c. Use of the permanent magnet flux enables sensitivity to be obtained with a low energy input as well as a high ratio of minimum operating current to continuous rating. The result is a reduced burden on the current transformers as compared with that when using an electromagnetic relay, with consequent simplification of design. The connections for one phase of a three phase generator using a relay as described are those shown in Fig. 15-35, these being repeated for each phase.

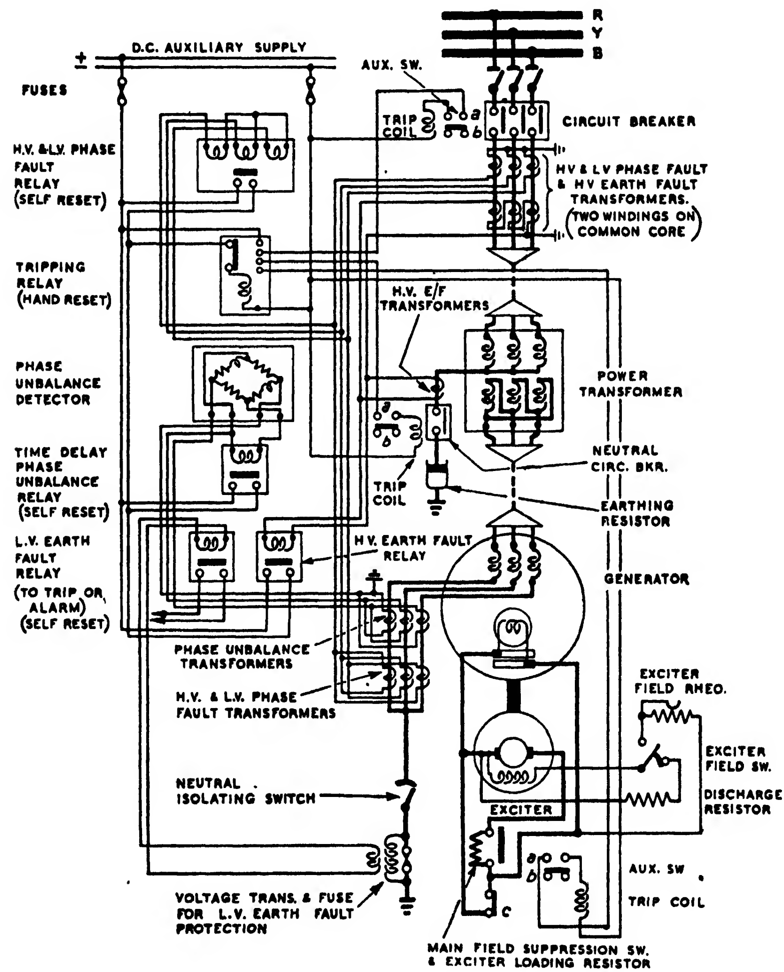


FIG. 15-36.—*Typical diagram of connections as Fig. 15-31 but for generator-transformer unit (Associated Electrical Industries Ltd.).*

In many large power stations each generator is tied in solid with an associated step-up transformer, there then being no switchgear at generator voltage. In such schemes, circulating current protection can be extended to cover both the generator and the transformer. A typical scheme is that shown in Fig. 15-36 which includes phase unbalance protection plus separate earth-fault protection for the l.v. and h.v. sides of the power transformer. In such a scheme there are difficulties to be overcome by reason of the dissimilar ratios, the characteristics of the current transformers during through-fault conditions, unbalance caused by transformer magnetising current and in all probability, tap-changing over a range of plus and minus 10% or so. Here, again, a biased scheme will counteract these effects and a scheme employing a biased relay of the type discussed is shown in Fig. 15-37.

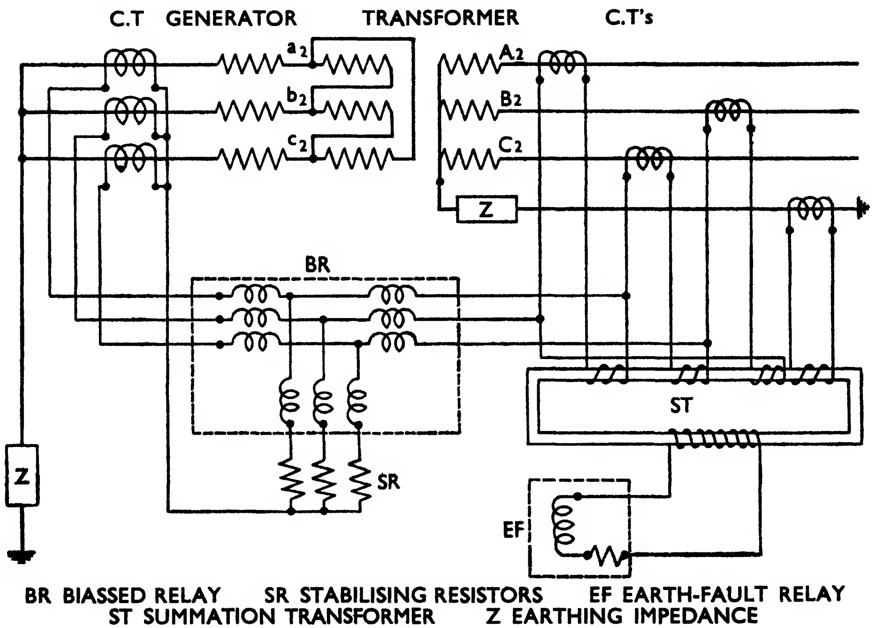


FIG. 15-37.—*Combined generator-transformer protection using biased differential relay with separate balanced restricted earth-fault protection for the earthed transformer star winding (Associated Electrical Industries Ltd.).*

This diagram indicates separate balanced earth-fault protection for the star connected h.v. transformer winding: whether earth-fault protection for the generator and low voltage transformer windings is applied additionally is a matter for separate consideration on its own merits.

Note in this diagram the stabilising resistors previously discussed and also how the current transformers on the secondary side of the power transformer are used not only for the circulating current protection but are also summated, along with the current transformer in the neutral, at a core-balance current transformer for earth-fault protection.

Circulating current protection can be applied on feeder circuits provided pilot wires are, or can be, made available between the two ends of the feeder. This is an obvious objection and often costly. If the feeder is long then the burden on the current transformers becomes excessive but in theory the scheme functions exactly as in our earlier description where one group of transformers at one end of the feeder compares the current at that point with that at the other end of the feeder where another group of current transformers is located. A difference exists, however, in that a relay is required at *both ends* of the feeder whereas for generator and transformer protection only one relay is employed.

A circulating current scheme using a biased relay at each feeder end is shown typically in Fig. 15-38 and here it will be seen that the relays are

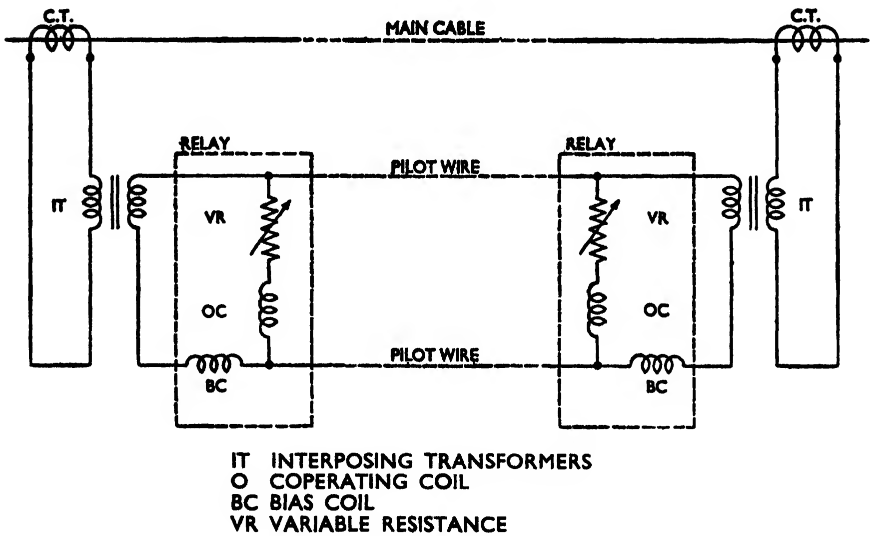


FIG. 15-38.—*Biased differential protection applied to a feeder circuit (The English Electric Co. Ltd.).*

energised via interposing transformers in order that the current circulating in the pilot wires is of low magnitude, an obvious advantage where the latter are of any length. Under normal or through-fault conditions, current circulates through the pilot wires and the relay bias coils but not through the operating coils. When a fault occurs on the feeder between the two groups of current transformers, and assuming the feeder runs to an open end, i.e. it is radial, then the current entering is greater than that leaving the feeder so that the current transformer outputs at the opposing ends do not balance. If the feeder can be fed from both ends, as for example in a closed ring main, then current will flow into the fault from *both* ends, and depending on the location of the fault, may be of equal magnitude. But in this case, the current flow at one end is in reverse to the normal direction

and the respective current transformer outputs will be out-of-phase, leading to a condition of unbalance. In both cases, therefore, there is the requisite condition of unbalance and this causes sufficient current to flow through the operating coils to overcome the restraint of the bias coils with consequent operation of the circuit-breakers at each end of the feeder.

This scheme, being discriminating, is equally suitable for parallel feeders, subject of course to the availability of pilot wires. It has the advantage over the scheme described earlier using I.D.M.T. relays in that time grading is unnecessary and, therefore, extremely rapid operation under fault conditions can be obtained.

The diagram in Fig. 15-38 is representative of one phase up to the interposing transformers. In practice, these are summation transformers having three primary windings on a common core fed from the three line current transformers. This summation transformer has only one secondary to feed a single relay element, as shown in the diagram, at each end of a three phase feeder. The adjustable resistors shown in each operating coil circuit ensure a suitable division of current between the two operating coils in the event of a fault fed from one feeder end only and thus ensuring that both relays operate to trip, noting that the setting of the operating coil depends upon the resistance of the pilot wire circuit.

Before leaving this discussion on differential protection it may be useful to consider briefly the need for some form of back-up protection. In all cases it can be assumed that such additional protection is applied to cover the possibility, however remote, of a failure on the part of the differential protection to operate with a fault within its zone, or the failure of circuit-breakers elsewhere on the system to clear local faults. Although busbar protection (see later discussion) is now employed in many large schemes, it is by no means universally applied and back-up protection on generators and transformers normally covered by differential protection, affords a means of protection against busbar faults, disconnecting the machine or transformer in such event. Back-up protection is usually afforded by I.D.M.T. relays, care being needed to ensure that time-discrimination is obtained in relation to the protective relays on the feeder network, the time setting on the back-up relay being higher than the highest setting of any feeder relay. Because of this, some difficulty may be experienced with an I.D.M.T. relay affording back-up protection on a generator circuit, as long before the time setting has been reached, the short-circuit current may have fallen to the steady state value due to decrement. It must therefore be ensured that the back-up relay will operate with this much-reduced value of current.

Under-voltage protection is not normally applied to circuits other than those which control motors. Here, it is essential to trip the circuit-breaker (or contactor) in the event of a supply failure and thereby prevent danger to personnel should the supply be restored without warning. In such cases, a deliberate action on the part of the operator is essential before the motor can be restarted. Under-voltage protection can be employed to provide an interlock to ensure, for example, that all rotor resistance is in circuit before starting a slip-ring motor by means of a drum controller or, where reduced-voltage starting is employed, e.g. auto-transformer, that full voltage is not applied to a stationary machine. Another aspect of under-voltage protection

is that where some external condition causes a serious but transient dip in voltage to occur. Depending on the drop-out value of the under-voltage trip coil or relay, this may cause unnecessary stoppages and, in such cases, it is feasible to time-delay the trip coil or relay for a short period. This may of course result in loss of speed and it may be that, due to the nature of the load, the motor will not pick up again.

Having now considered some relatively simple and commonly used forms of protective gear, we may usefully note, if only briefly, further protective details and schemes as applied to generator, transformer and feeder circuits and for busbar protection. Some of the schemes we shall note are developments based on the circulating current principle, while others are those which have been designed especially to meet conditions arising out of modern high-voltage power transmission and interconnected power networks such as the Grid, where high-speed operation, transient stability and other characteristics are essential. It will be convenient to consider these further details and schemes under headings corresponding to those noted above.

GENERATOR PROTECTION

Some of the faults which may occur on an a.c. generator in service are:—

(a) Failure of insulation on stator windings or associated connections.
(b) Failure of insulation on rotor.
(c) Overspeed.
(d) Generated over-voltage.
(e) Unbalanced loading.
(f) Field failure.
(g) Failure of prime mover.

Stator winding faults comprise short-circuits between phases or to earth, and short-circuits between turns, the latter rapidly developing into earth-faults. It is essential that the main circuit-breaker between the machine and the busbars be opened immediately when a stator fault occurs so that other generating plant on the system can be prevented from feeding into the faulty machine. At the same time it is necessary to suppress the rotor field to prevent the machine itself from feeding into the fault. If the neutral of the machine is earthed through an automatic circuit-breaker, it is an advantage to provide for the opening of this circuit-breaker and thereby assist with rapid clearance of earth-fault current.

The minimum primary operating current at which the earth fault protective gear operates governs the amount of stator winding protected and, in the case of machines operating on a system in which the neutral point is earthed through a resistance, the value of the earthing resistance and the minimum operating value of the protective gear must be co-related to give the maximum degree of stator winding protection (see Chapter XX).

For phase faults, overcurrent or some form of differential protection or a combination of both, can be applied. When both are applied, the overcurrent relays will act as back-up protection as previously discussed. Earth-fault protection should be of the restricted type sensitive to earth-faults in the stator winding or in the associated connections and not to earth-faults outside the zone of protection.

In conjunction with this protective gear, provision has to be made to

suppress the field in the shortest possible time after an internal fault has been detected. The method of achieving this is to cause automatic opening of a suitable switch or circuit-breaker in the field circuit, as shown in Fig. 15-39.

It will be seen here that the trip-coil circuit on the field switch is completed by auxiliary contacts on the protective relay. The opening of this switch results in high rotor voltage and, in the case of built-up or laminated

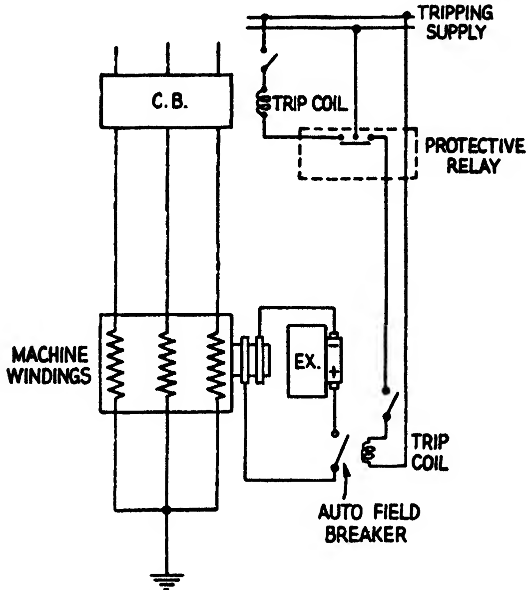


FIG. 15-39.—*Simplified connections for automatic field suppression.*

rotors, this may cause insulation failure and a field discharge resistance must therefore be used (see Fig. 15-31). When a solid rotor is used the effect is not usually dangerous and resistance is not normally employed noting that the use of resistance slows up the process of field suppression.

Failure of insulation on the rotor is usually in the form of a single fault to earth and only in the remote possibility of a double fault is damage likely. On very large generators it is often considered advisable to provide some form of earth-fault detector, as a second fault to earth occurring in another part of the field winding constitutes a short-circuit requiring an immediate shut down of the machine. A suitable detector is an earthed negatively-biased relay connected between the field circuit and earth as shown in Fig. 15-40 and discussed in more detail in an article by Newcombe on the protection of large generator units (see bibliography).

Overspeed (leading to overvoltage) may arise due to a sudden loss of load. In certain circumstances (e.g. total loss of load coupled with high steam pressure at the stop-valve) the rise in speed may be so considerable

that the action of the governors or the closing of the emergency valve will not prevent the rise. Some form of overspeed device must therefore be provided to safeguard the machine under these circumstances and arranged to trip the main circuit-breaker.

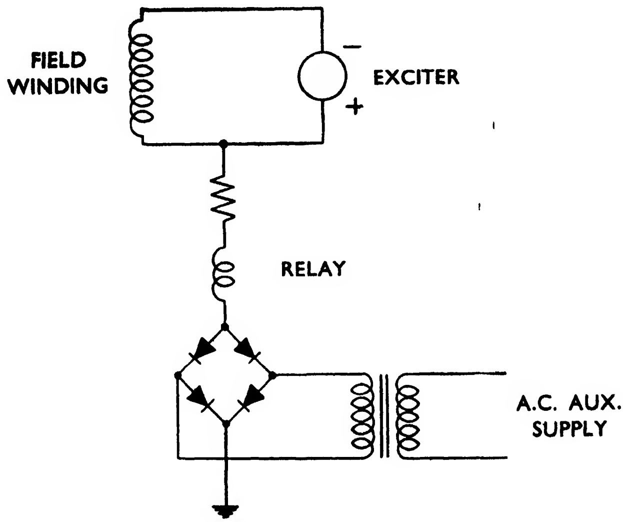


FIG. 15-40.—*Rotor earth-fault detection by negative biasing method.*

Generated overvoltage of significant duration or magnitude does not generally occur on turbo-generator equipments and it is not usual to provide protection against such conditions. In the case of hydro-electric generators, however, the inherent slow action of the control governors gives a considerable lapse of time before normal speed is restored after a sudden loss of load to the system. The increase in speed due to loss of load gives a corresponding increase in voltage, which may lead to damage of connected apparatus and will over-stress the insulation of the generator winding. Some form of protection is therefore recommended for such generators. It should be arranged to disconnect the machine from the system and to open the field system if the generator voltage rises 20% above normal.

Unbalanced loading arises from causes such as faults between two lines or one line to earth on the system external to the generator. The unbalanced currents, even though of a value much less than the rated normal current of the machine may give rise to dangerous overheating in the rotor. Protection can be given against such conditions by the use of negative phase sequence protection in which a filter network detects the flow of negative phase sequence currents in the generator windings, and not responsive to balanced conditions, i.e. to positive phase sequence currents.

In Chapter IV we have shown that any unbalanced system can be considered to be comprised of three balanced systems as follows:—

(1) A three phase system of forward phase sequence known as the "positive phase sequence".
(2) A three phase system of reverse phase sequence, known as the "negative phase sequence", and
(3) A system without time interval between vectors, known as the "zero phase sequence".

It has also been shown that:

(a) The positive component only is present with balanced three phase conditions and corresponds to normal load conditions.
(b) The positive and negative components are both present with unbalanced phase to phase conditions corresponding to faults between lines.
(c) The positive, negative and zero components are all present with unbalanced phase to neutral conditions corresponding to a line to earth-fault on a system with an earthed neutral.

From the foregoing, it will be noted that the negative phase sequence component is present in *both* conditions likely to produce unbalance in a three phase system and, therefore, a relay that is sensitive to this component and not to the positive component will protect the machine against conditions of single phase loading.

An equipment designed for this purpose is shown in Fig. 15-41 comprising a filter network with matching transformers and a relay unit consisting of a heated body, a sensitive relay responding to the temperature of the heated body and an instantaneous alarm relay element.

In this scheme the output from the filter network is fed into a small coil of resistance wire and so raises its temperature. By suitably proportioning the heated body, its time/current characteristic for a given temperature rise is made to match the ability of the protected generator to withstand the flow of negative phase sequence currents. When the temperature of the heated body reaches a given level a sensitive relay element, connected to a thermocouple, operates.

The alarm relay, connected directly to the matching transformer, closes its contacts to give early indication of an unbalanced condition and in the case of low values of negative phase sequence current, the control engineer has an opportunity to take action before circuit-breaker tripping occurs. The latter can only take place when the contacts on *both* the alarm and temperature responsive relay are closed.

With regard to *failure of the prime mover*, in the case of a turbo-generator, no serious effect will be sustained by allowing the turbine rotors to be motored by the generator running as a synchronous motor for a short time provided the lubricating system etc., continues to function. In the case of back-pressure turbo generators, however, protection against inverted running should be included. On such machines, after closing the combined emergency and stop valves upon failure of the prime-mover the generators should be disconnected from the busbars, otherwise the turbine rotors would be rotating in trapped steam of back pressure density which would cause a dangerous increase in temperature of the rotor and casing.

Diesel-engine driven alternators should also be protected against

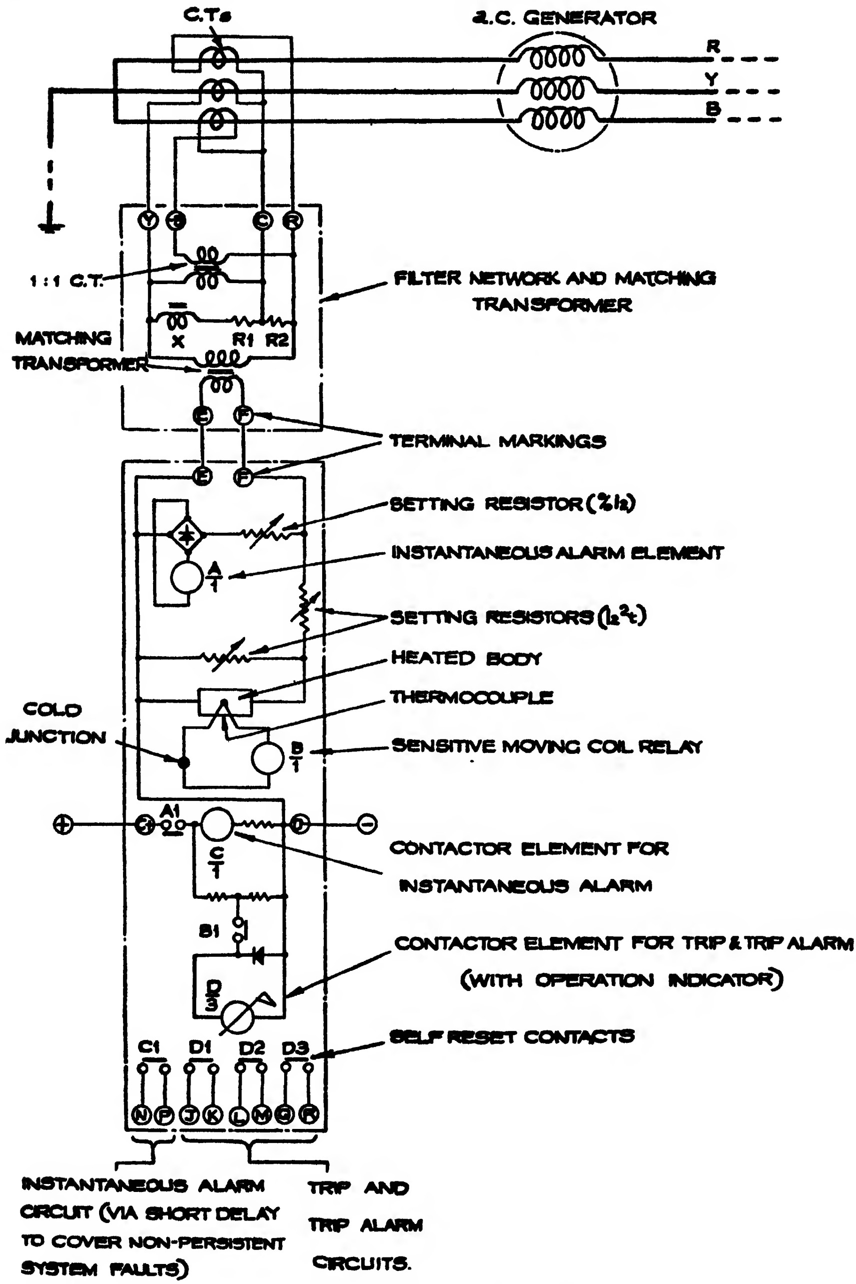


FIG. 15-41.—*Schematic diagram of negative phase sequence protective gear (The General Electric Co. Ltd.).*

inverted running to guard against motoring in the event of a mechanical seizure.

When a prime mover fails, there is a reversal of power in the stator winding and protection can be afforded by the use of a single pole reverse power relay with an inverse definite minimum time delay of, say, 1 second.

TRANSFORMER PROTECTION

When a fault occurs within a transformer (or other oil-filled equipment such as reactors or capacitors), heat is produced which in turn liberates gases from the oil either gradually or violently according to the nature of the fault. If the apparatus is fitted with an oil conservator a gas-activated relay fitted in the pipe connection between the main oil tank and the conservator can be arranged to indicate the presence of the gases firstly by completing an alarm circuit and secondly to cause the controlling circuit-breaker(s) to trip out. This form of protection is known as "Buchholz" and a typical relay is shown in Fig. 15-42.

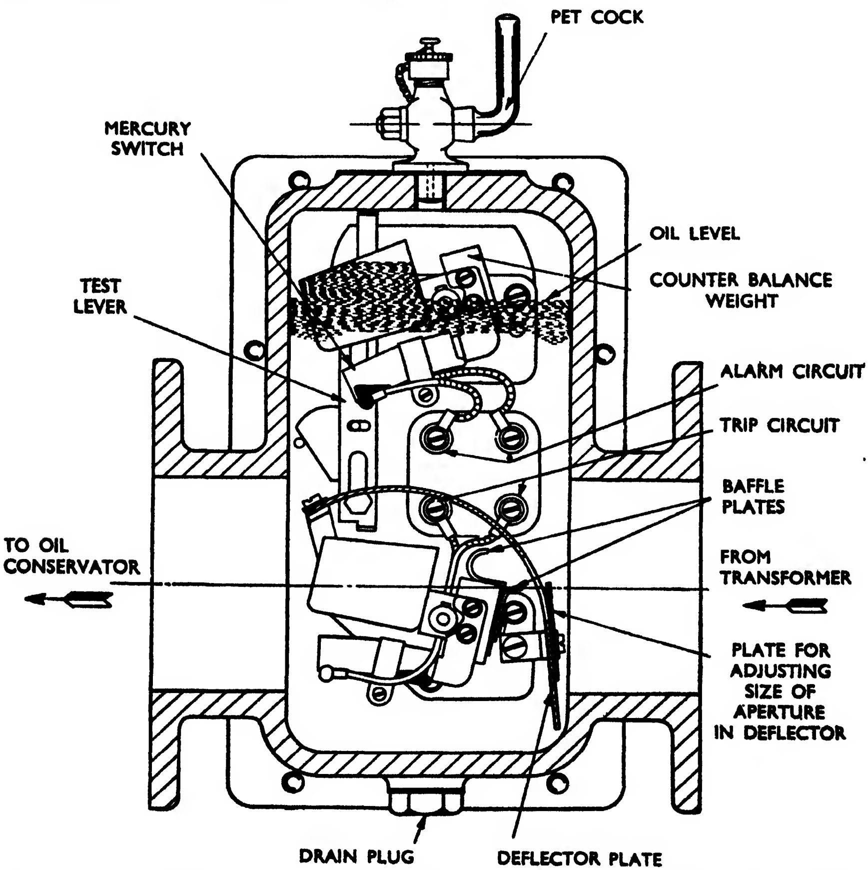


FIG. 15-42.—*Diagrammatic illustration of "Buchholz" relay with alarm circuit closed (The English Electric Co. Ltd.).*

In this relay each of the two chambers houses an oil bucket with mercury switch attachment. Each bucket is kept level under normal conditions by a balance weight and the mercury switches will be open. When a slight or incipient fault occurs in the transformer, small bubbles of gas will be generated and these, attempting to pass from the tank to the oil conservator, will be trapped in the relay housing.

As this gas accumulates, the oil level in the relay will fall, leaving the top bucket full of oil. As this bucket will not now be fully immersed, the extra weight due to the contained oil will overcome the balance weight and cause the whole assembly to tilt, thereby causing the mercury switch to close and complete the alarm circuit. When a serious fault occurs, the gas generation is rapid, causing the displaced oil to surge through the relay. This oil flow will impinge on the baffle plates and cause the bottom bucket assembly to tilt, closing the mercury switch in the trip circuit to the breakers.

If a transformer suffers a loss of oil, causing the oil level to drop below the level of the relay, the buckets of the two elements will be left full of oil and first the alarm and then the surge element, will operate to close the alarm and trip circuits.

The use of a "Buchholz" relay on transformers is generally recommended for units above about 1 000 kVA where these are fitted with conservators, as by this means incipient faults can be detected before great damage is caused.

In our earlier discussion concerning circulating current (differential) protection we noted various problems such as—

(a) The currents on opposite sides of the transformer differ in phase angle and magnitude depending on the inter connection of windings and the transformer ratio.

(b) The transformation ratio is often variable as governed by tap-changing equipment.

(c) The magnetising current inrush on switching in appears only on the primary side and has no counterpart on the secondary side. The differential protection, therefore, detects this as an internal fault and causes unwanted tripping of the circuit-breaker. This inrush current can attain a magnitude many times the steady state magnetising current which may be as low as two to four per cent of the normal full-load current. (See the J. & P. Transformer Book and Fig. 15-60.)

We have seen how (a) and (b) can be overcome by using a differential protective system with biased relays (the G.E.C.-McColl patents on such schemes date back to 1920) and problem (c) can be taken care of by having time delayed relays to ensure stability. Unfortunately, this time delay is also operative when an internal fault occurs on a transformer and when it should be isolated from the system as quickly as possible.

It is in an effort to overcome all these problems and yet retain the ideal of the differential protection scheme with its discriminating features, but with high-speed operation, that a number of transformer protective schemes have been perfected of which the following are examples.

In a scheme known as magnetic-balance protection (Associated Electrical Industries Ltd.), two forms are available, one a plain magnetic-balance for transformers without tappings, and the other a self-stabilising magnetic-balance foı use where there are tappings, either on-load or off-load.

The operation of the plain magnetic-balance system will be understood by reference to Fig. 15-43. At (a) is shown (one phase for simplicity) a power transformer with current transformers of appropriate ratio in the high-voltage and low-voltage lines, having their secondaries connected in series. This is a conventional circulating current scheme but the relay is not shown.

The currents circulating in the secondaries of these current transformers are identical and, in each, the ampere-turns of the secondary and primary will be nearly equal, any difference being due to the magnetomotive forces necessary to magnetise the core. Since the secondary turns of the current transformers are proportional to their respective primary currents, these

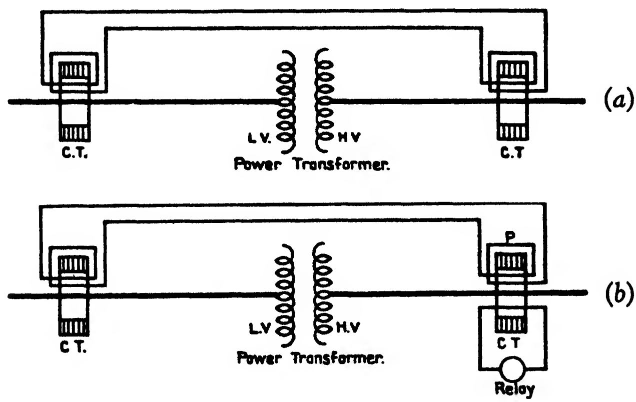


FIG. 15-43.—*Diagram illustrating plain magnetic-balance system (Associated Electrical Industries Ltd.).*

magnetising forces will be similarly proportional to the primary currents. Therefore, since the current transformer on the high-voltage side has less secondary turns and has a smaller primary current than that on the low-voltage side, it is subject to less magnetisation. This means that the total voltage drop occurring in both current transformer secondaries and the interconnecting leads will be supplied mainly by the current transformer on the low-voltage side.

In practice, the current transformer on the low-voltage side is made to take the whole of this burden and to have a magnetising current of an insignificant amount. Consequently, the current flowing in the secondary of the current transformer on the high-voltage side provides a magnetomotive force equal and opposite to that of its primary, and the core is unmagnetised under all through-current conditions—hence the name "Magnetic-balance." If a further winding is added to the current transformer on the high-voltage side, as in Fig. 15-43 diagram (b), no voltage will be induced in it under healthy conditions, and the associated relay remains inoperative.

However, under fault conditions within the protected zone, the magnetomotive forces of the primary and the secondary of the current transformer on the high-voltage side will not neutralise, but will induce a voltage to

operate the relay. In the case of a fault fed from one side only, this voltage is induced directly whilst, for a fault fed from both sides, the magnetomotive forces will be additive due to the change in direction of current flow on one side. The total ampere-turns tending to operate will be proportional to the fault current; part of these will magnetise both sets of current transformers and the remainder will cause current to flow in the additional relay winding.

A particular advantage of this magnetic-balance system is that high-permeability alloy can be used to effect a very large reduction in the magnetising-current of the current transformer on the high-voltage side and, consequently, a greatly improved sensitivity can be obtained. Under through-fault conditions this current transformer is unmagnetised so that the early saturation characteristic of such material does not reduce the stability obtainable. The use of high-permeability alloy also permits the use of an instantaneous type relay because the d.c. component of the magnetising current, present during switching operations, on either the low-voltage or

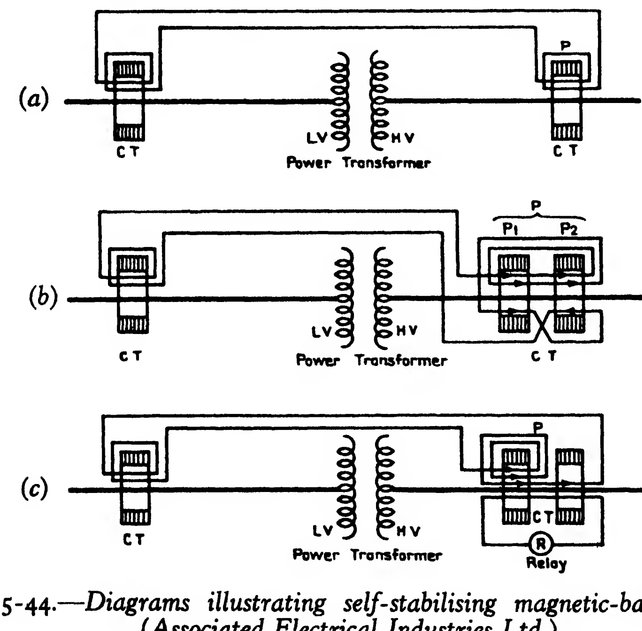


FIG. 15-44.—*Diagrams illustrating self-stabilising magnetic-balance system (Associated Electrical Industries Ltd.).*

high-voltage side of the power transformer, can be effectively suppressed.

A further advantage is that the sensitivity is entirely independent of the secondary current normally circulating between the two sets of current transformers, so that this may be made as low as possible, and the adverse effect of load burden on stability is eliminated.

When a power transformer is provided with tappings, there occurs a change in current values which, unless compensated for by equivalent

tappings on the protective current transformers, will upset the state of balance essential in a circulating current scheme of protection. As noted earlier, it is inconvenient to have to change the turns ratio of the current transformers every time a tap change on the power transformer takes place, and other means are necessary to counteract the out-of-balance effect.

In the self-stabilising magnetic-balance system this is achieved by splitting the cores of the current transformers on the high voltage side into two parts and by arranging the secondary windings on these split cores so that under healthy conditions the magnetomotive force from one half-core—tending to induce volts across the relay winding—is neutralised by the magnetomotive force from the other half-core. Under fault conditions within the protected zone, operation occurs in exactly the same manner as in the plain magnetic-balance scheme.

Fig. 15-44 diagram (a) shows the ordinary magnetic-balance system of Fig. 15-43, with the relay winding removed from the current transformer, P, on the high voltage side for clarity. Diagram (b) shows the core of transformer P divided into two halves, P1 and P2, and with additional cross-turns in series with the secondary, added in opposite senses on each half. The transformer P, retains the magnetic-balance principle since the additional cross-magnetising turns result in equal and opposite fluxes in the two half-cores which together induce no resultant voltage in the relay winding. The magnetisation characteristic of the half-cores, P1, and P2, of transformer P, when energised from these differential windings is shown in Fig. 15-45. When carrying normal full-load current the two half-cores are subject to equal and opposite magnetomotive forces at respective points, A, due to the differential windings but, if the transformer is operating at some tap other than normal, the individual half-cores will operate at A1 and A2 due to the resulting action of the primary and ordinary secondary ampere-turns (i.e. the out-of-balance ampere-turns due to the change in tap positions). In magnitude this will be additive for one half-core (AA2), and subtractive (AA1) for the other. Consequently, the relay winding will be energised to an extent directly proportional to the algebraic sum of the resulting fluxes Oa1 and Oa2. This is indicated by the ordinate at A in Fig. 15-46. With an increase in the main current the respective magnetomotive forces move to points B1 and B2, and the relay is energised to an extent proportional to the algebraic sum of Ob1 and Ob2 (indicated by the ordinate at B in Fig. 15-46). Further increase to points C1 and C2 in Fig. 15-45 brings about a decrease in the resulting voltage induced in the relay circuit, as shown by the ordinate at C in Fig. 15-46. Consequently, for any given tap position, the available induced voltage for relay operation is variable with the primary through current, as shown by the typical curve in Fig. 15-46. If, therefore, the relay is set for an operating voltage above the maximum ordinate of this curve, the protective system will always remain stable.

In practice the design is such that when the maximum tap out-of-balance occurs on the power transformer, the maximum induced voltage does not exceed one-half of that necessary to operate the relay. Fig. 15-46 also shows for comparison the relay characteristic for plain magnetic-balance (or circulating current protection) under tap unbalanced conditions: it will be noted that the relay voltage increases in proportion to the primary through current and would give rise to false operation at the point D.

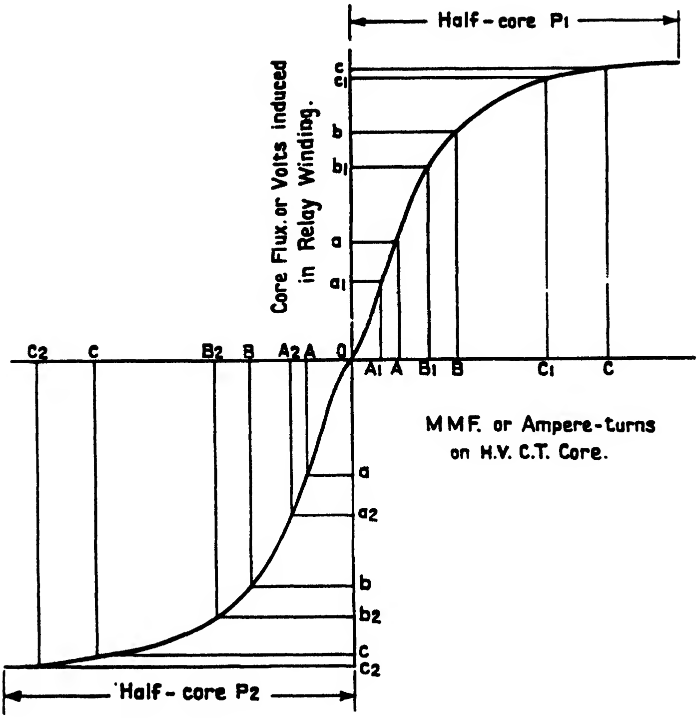


FIG. 15-45.—*Magnetisation characteristics of current transformer "P" in Fig. 15-44. (Associated Electrical Industries Ltd.).*

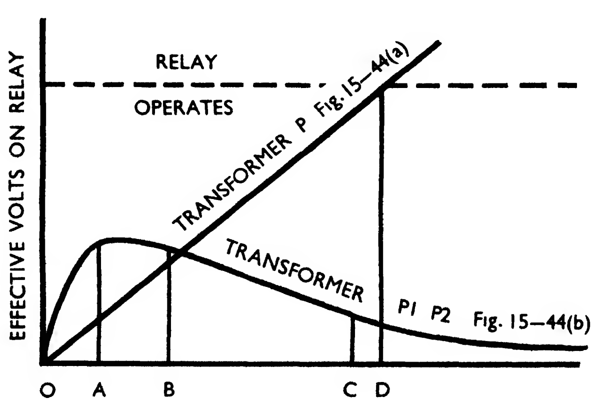
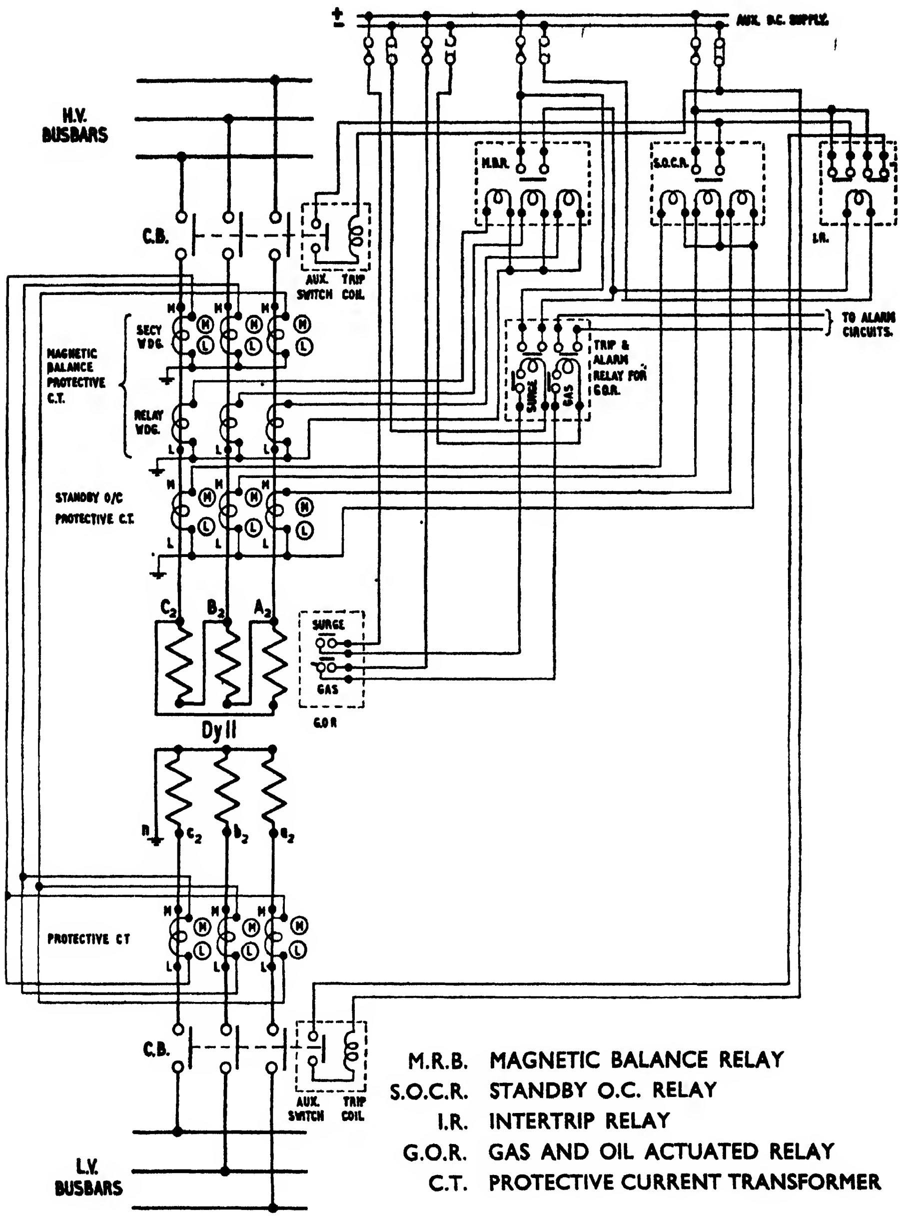


Fig. 15-46.—*Magnetic-balance protection—induced voltages at relay (Associated Electrical Industries Ltd.).*



M.R.B. MAGNETIC BALANCE RELAY
S.O.C.R. STANDBY O.C. RELAY
I.R. INTERTRIP RELAY
G.O.R. GAS AND OIL ACTUATED RELAY
C.T. PROTECTIVE CURRENT TRANSFORMER

Fig. 15-47.—*Diagram showing magnetic-balance protection for delta/star connected transformer with Buchholz and standby overcurrent protection.* (*Associated Electrical Industries Ltd.*).

Under fault conditions within the protected zone, the magnetomotive forces of the primary and ordinary secondary turns of transformer, P (Fig. 15-44) diagram (b), do not neutralise, and energise the relay as in the case of plain magnetic-balance, whilst those due to the additional cross-turns produce no resultant effect in the relay circuit.

The practical equivalent of Fig. 15-44, diagram (b) is Fig. 15-44 diagram (c), which shows the relay winding reinstated and the other windings combined to give an unequal number of turns on each half-core.

The full diagram of connections of this type of protective gear applied to a three phase delta/star transformer is shown in Fig. 15-47.

The magnetic-balance principle can be applied to protective schemes for combined generator/transformer units, to Scott-connected and other special transformers and can be combined with restricted earth-fault protection for transformers.

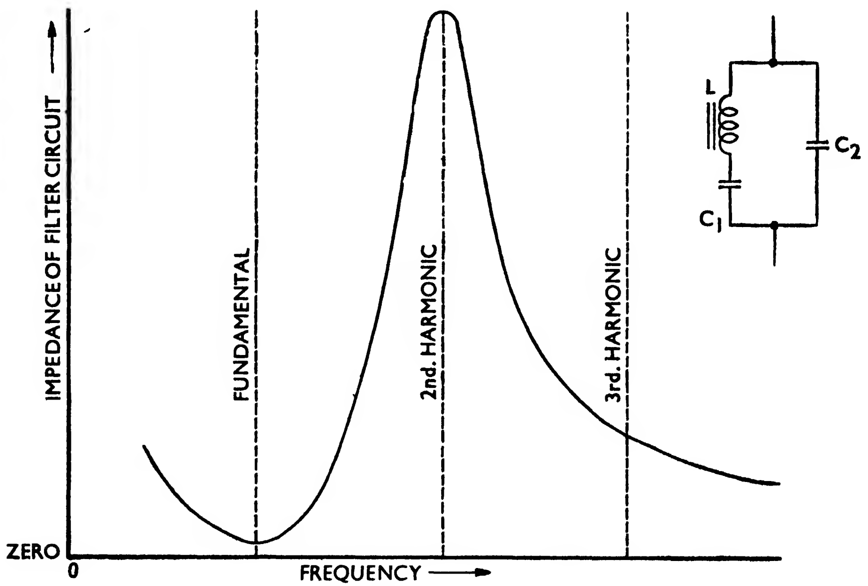


FIG. 15-48.—*Variation in filter network impedance with frequency (The General Electric Co. Ltd.).*

In other high-speed schemes of differential protection which have been introduced recently a feature known as "harmonic restraint" has been employed to overcome the problems previously noted. In these schemes use is made of the fact that the nature of the current obtaining during the magnetising current inrush period is different from that due to an internal fault condition, insofar that the former contains a predominant second harmonic whereas the latter is essentially sinusoidal (with or without a d.c. transient component) and having negligible harmonic content. At high internal currents, however, when the current transformers may saturate, a third harmonic component may be present in the relay circuit.

From the foregoing it will be clear that if a circuit can be devised in which the protective relay is restrained when the second harmonic is present, but is free to operate at the fundamental frequency or when the third harmonic is present, then the protective system will not be subject to unwanted operation due to magnetising inrush currents. To produce this result it is necessary to provide a filter or acceptor network suitably tuned to fundamental frequency and if this network is incorporated in a circuit employing

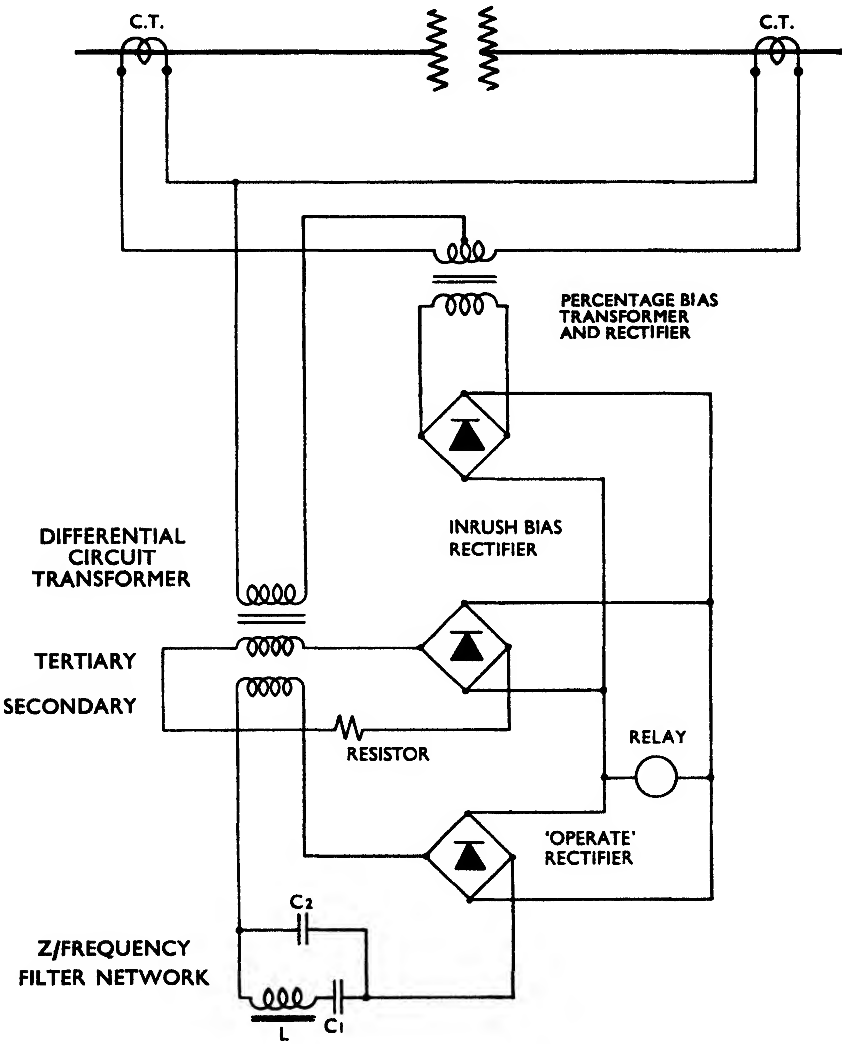


FIG. 15-49.—*Single phase diagram of differential biased protective scheme with harmonic restraint for transformer circuit (The General Electric Co. Ltd.).*

a sensitive relay of the permanent magnet moving-coil type, d.c. operated, together with bias to cover the effects of tap changing, the result can be a high-speed protective scheme which solves all the problems previously noted.

This, then is, very briefly, the principle on which schemes we shall describe are based.

The first of these is one developed by The General Electric Co. Ltd., and designated Type ZTB in which the harmonic filter circuit has two-frequency tuning and employs a single fault detecting relay of the sensitive polarised type. How the impedance of the filter circuit varies with frequency is shown in Fig. 15-48 and the principles on which the complete protective system operates are best studied from Fig. 15-49, which shows the biasing arrangements in single phase for simplicity.

Two transformers are employed, one, with a centre-tapped primary, is in series with one of the pilot wires, while the other is in the differential circuit across the pilots. The centre-tapped transformer is energised by the circulating current in the pilots and has an output proportional to the through load or fault current. This output is used to bias the relay, increasing its setting to ensure that operation will not occur on through-faults when "spill" currents will flow in the differential circuit due to current transformer inequalities as previously described and depending on the power transformer tapping in use.

The other transformer is energised by current flowing in the differential circuit and has secondary and tertiary windings. The secondary winding is connected to a rectifier whose output tends to cause relay operation, while the tertiary is connected to another rectifier which is used to bias the relay.

A third rectifier is fed via the filter network in which the inductance L and the capacitor C_1 are tuned to the fundamental frequency to form a low impedance acceptor circuit. At a frequency of double the fundamental, L and C_1 together act as an inductance which resonates with the capacitor C_2 to form a second harmonic rejector circuit. Thus current at 50 cycles is accepted and that at 100 cycles is rejected.

With a given current through the primary winding of the differential circuit transformer, the proportion of current between the secondary and tertiary windings will depend upon the relative impedances fed by these windings.

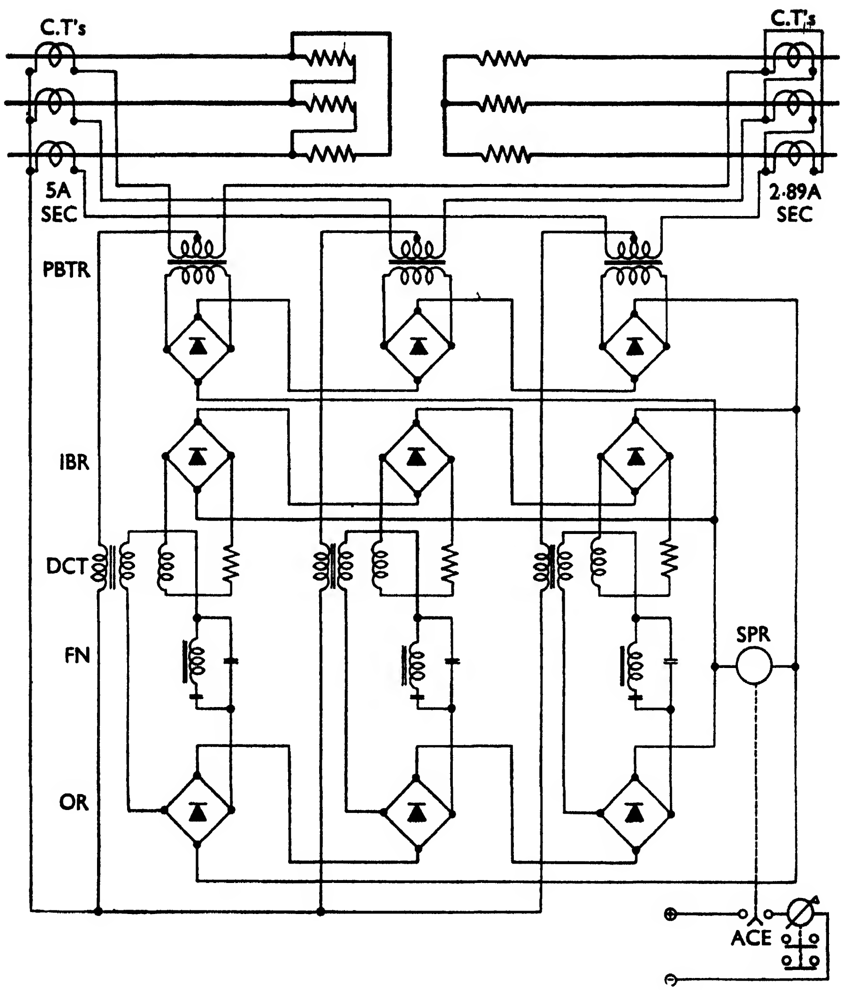
The circuit parameters of the circuit can be so proportioned that:—

(a) With fundamental current input the greater part of the output current will flow in the secondary winding to operate the relay.

(b) With second harmonic current the tertiary winding will have a large output to produce a heavy bias against relay operation.

(c) With third harmonic current the secondary and tertiary currents will be similar, cancelling out to produce negligible restraint on the relay.

The operate and bias current outputs from the three rectifiers are connected in a simple circulating current circuit and a polarised, moving-coil relay is connected across the rectifiers such that if the operate current exceeds the bias current, input current will flow through the relay in the direction required to operate it. When the bias current predominates then



PBTR PERCENTAGE BIAS TRANSFORMERS & RECTIFIERS
IBR INRUSH BIAS RECTIFIERS
DCT DIRECTIONAL CIRCUIT TRANSFORMERS.
FN FILTER NETWORKS.
SPR SENSITIVE POLARISED RELAY.
OR "OPERATE" RECTIFIERS.
ACE AUXILIARY CONTACTOR ELEMENT.

FIG. 15-50.—*Biased differential protection with harmonic restraint applied to a three phase delta/star transformer (The General Electric Co. Ltd.).*

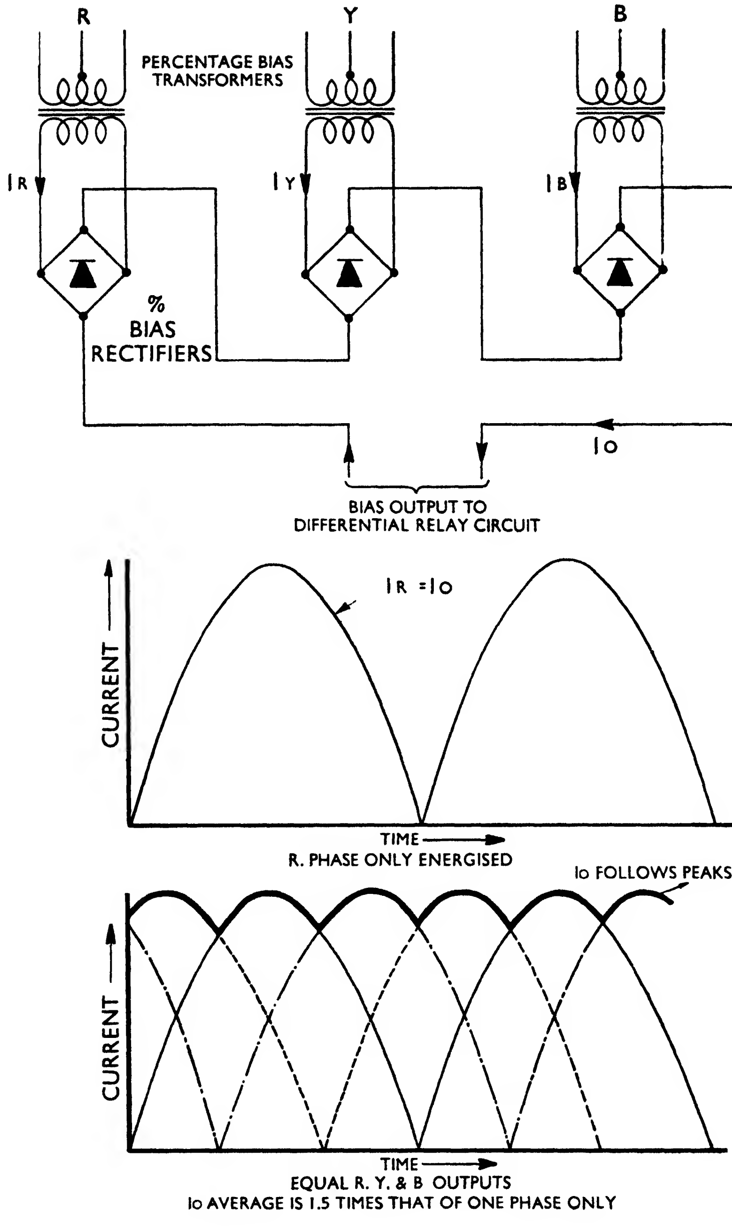


FIG. 15-51.—*Showing series connection of R.Y.B. rectifiers (diagram shows those for percentage bias) (The General Electric Co. Ltd.).*

the current in the relay flows in the reverse direction and will hold the movement against a backstop.

In a three phase arrangement, shown in Fig. 15-50, each phase has its own percentage bias and differential circuit transformers, filter circuit and set of three rectifiers. The red, yellow and blue phase rectifiers of each purpose are connected in series as shown typically for the percentage bias rectifiers in Fig. 15-51. With this circuit, the output current Io from the group of three rectifiers will, at any instant, correspond with the maximum current obtaining in any one phase. A single relay provides for three phase protection and is subjected to the biasing effects of the phase carrying the greatest through current and/or second harmonic current at any instant and to the operating effects of the phase carrying the greatest fundamental frequency current in its differential circuit. An inherent characteristic of this circuit is that on through three phase faults the relay biasing is 1·5 times that produced by line to earth or line to line faults of the same magnitude and similarly, the relay has 1·5 times the sensitivity to three phase internal faults than to other faults.

The second scheme we shall note is one due to Associated Electrical Industries Ltd., in which a relay (designated "Stabilay") of the three-element pattern is used. Each element consists of a permanent magnet moving-coil unit, shown in Fig. 15-52, and in which three coils are wound on a light-weight cylindrical metal former suspended horizontally between the concentric poles of a permanent magr.et. The three coils are used respectively for "differential operation", "harmonic current restraint" and "percentage-

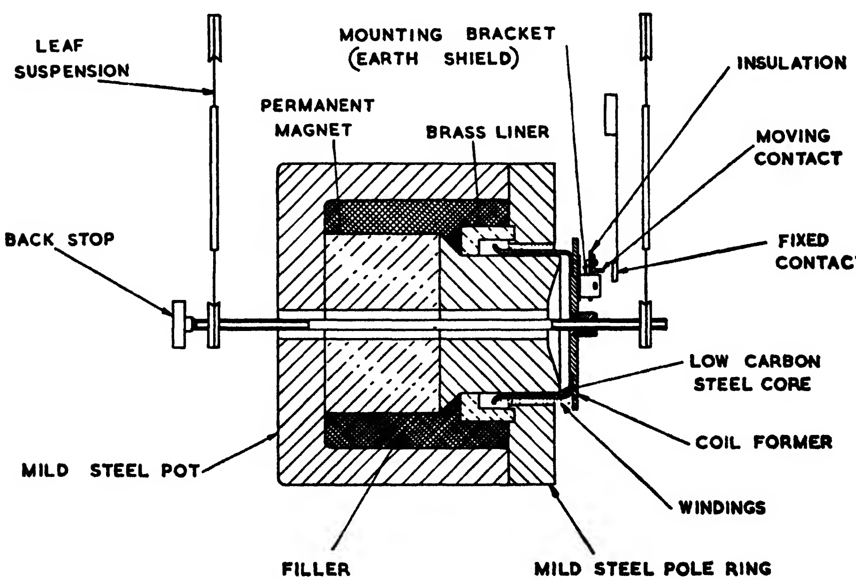
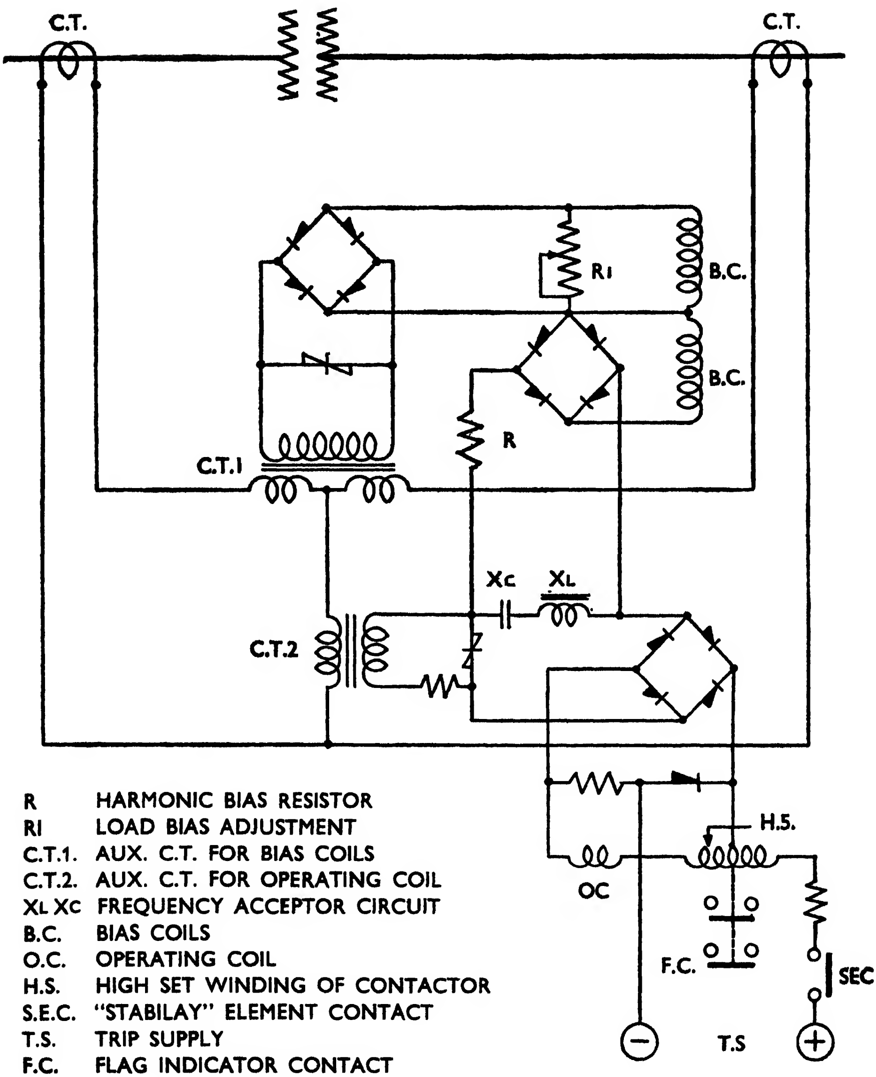


Fig. 15-52.—*Cross-sectional view of "Stabilay" relay element (Associated Electrical Industries Ltd.).*



R	HARMONIC BIAS RESISTOR
RI	LOAD BIAS ADJUSTMENT
C.T.1.	AUX. C.T. FOR BIAS COILS
C.T.2.	AUX. C.T. FOR OPERATING COIL
XL XC	FREQUENCY ACCEPTOR CIRCUIT
B.C.	BIAS COILS
O.C.	OPERATING COIL
H.S.	HIGH SET WINDING OF CONTACTOR
S.E.C.	"STABILAY" ELEMENT CONTACT
T.S.	TRIP SUPPLY
F.C.	FLAG INDICATOR CONTACT

FIG. 15-53.—*Single phase diagram of percentage differential protection with harmonic restraint applied to a two-winding transformer (Associated Electrical Industries Ltd.).*

differential restraint" and being energised by direct current, many of the problems associated with alternating currents are simplified, the characteristics being naturally linear. Because the working flux is supplied by the field-magnet system the energy to be provided by the coil winding is small, making possible a large ratio of minimum operating current to continuous rating, together with a reduction in the burden imposed on the current transformers due to the low impedance of the coil. This relay has been discussed in greater detail in a paper by Ryder, Rushton and Pearce (see bibliography).

Fig. 15-53 shows one phase of this protective scheme (the other two phases are similar) applied to a two-winding transformer. An acceptor circuit Xc and XL tuned to the fundamental frequency, is connected in series with the relay operating coil, the voltage developed across this tuned circuit being connected through a resistor to energise the restraining coil on the relay. For currents of fundamental frequency (e.g. fault currents)

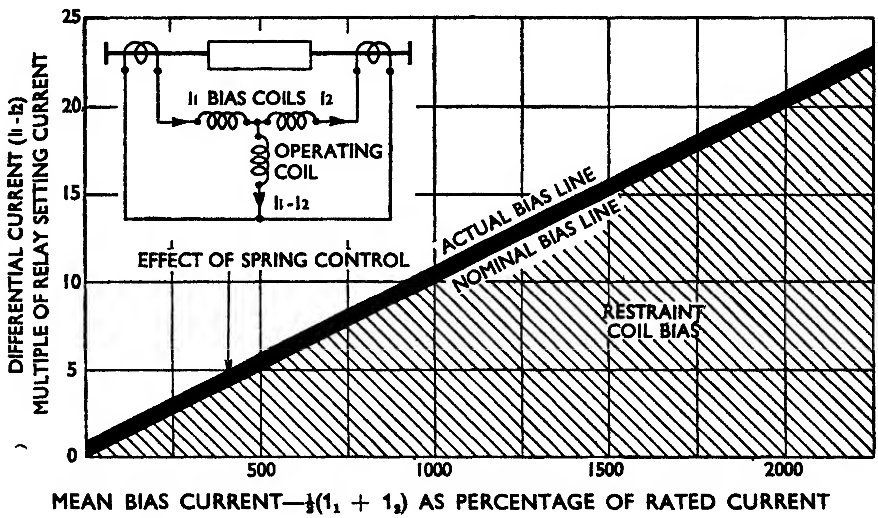


FIG. 15-54.—*Restraint characteristic for biased differential relay having equal percentage setting and bias (Associated Electrical Industries Ltd.).*

the tuned circuit has a low impedance and thus effectively short circuits the bias coil. For harmonic currents the impedance of the tuned circuit is greater and a high proportion of the operating coil current is passed through the bias coil. The ratio of operating-coil turns to bias-coil turns is arranged to ensure adequate restraint during the magnetising current inrush period. The resistor in series with the harmonic restraint coil is preset and ensures adequate restraint for the most severe switching surges.

The percentage bias feature in this scheme is derived from the auxiliary current transformer connected in one of the pilot wires between the primary and secondary line current transformers thus carrying the through-current.

The auxiliary transformer secondary output is fed to the percentage bias coil through its associated rectifier, across which is connected an adjustable resistor to give a continuously variable adjustment on a calibrated scale of the percentage bias slope. Fig. 15-54 shows this slope characteristic. As noted in earlier discussion, imperfect matching of current transformers and the effect of tappings on the power transformer invariably leads to some "spill" current flowing in the operating coil current when a heavy through-fault condition arises, this current being represented by $I1-I2$ in the inset diagram Fig. 15-54, and this can only cause relay operation when the operating bias current ratio for which the relay is set is exceeded. The magnitude of the current to cause operation is not constant, but automatically increases as the circulating current increases and a definite ratio exists between the two quantities. The curve Fig. 15-54 shows the differential current $(I1-I2)$ related to the mean circulating current $[(I1+I2)/2]$ as a percentage of rated current. In the illustration the "nominal bias line" is that due to spring restraint and at low values of mean circulating current this exercises over-riding control but at larger values it becomes relatively unimportant and the "actual bias line" approaches the "nominal bias line", the slope of which is the adjustment. The relay will be operative for conditions above the "actual bias line" and inoperative for conditions below it. The choice of per cent bias must be based on the per cent unbalance on overload for which stability is desired and "per cent bias" is defined as the ratio of out-of-balance current to the mean circulating current (expressed as a percentage) for which the relay would operate with zero spring control.

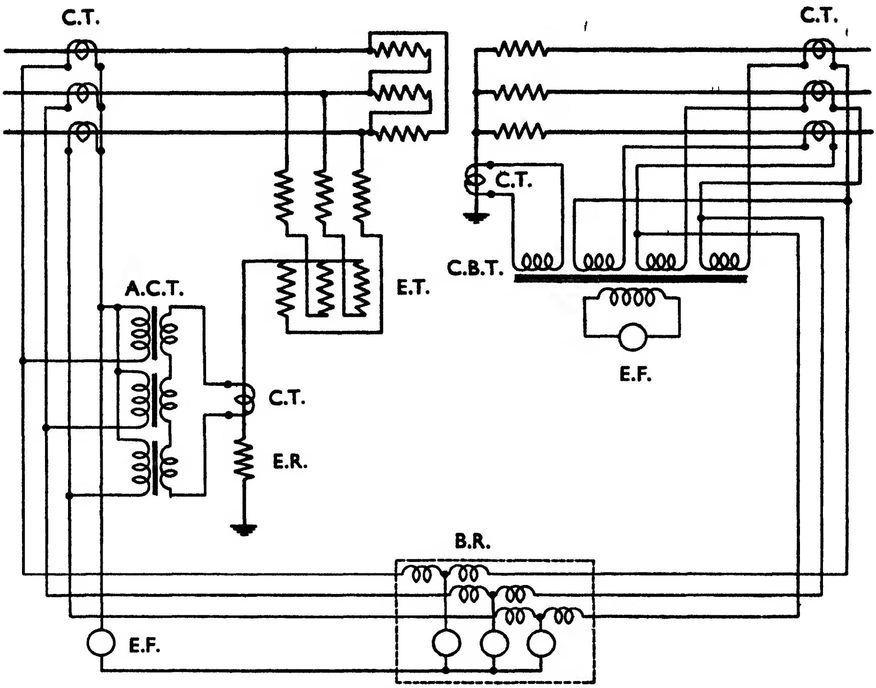
When it is required to apply restricted earth-fault protection to one or both windings of a two-winding transformer, in addition to the differential protection, this can be combined as shown in Fig. 15-55 to show a considerable economy in the number of line current transformers required. It is important, however, that the line current transformers satisfy the requirements of both schemes.

In another scheme, known as "Duo-bias" (A. Reyrolle and Co. Ltd.), the basic principle of current balance has been maintained, but with features incorporated to produce a percentage-bias to prevent operation by out-of-balance currents due to tap changing and current transformer inequalities and a transient-bias to give stability with magnetising inrush currents, the latter, as we have seen earlier, containing a strong second harmonic and used to provide a biasing feature.

The relay used in this scheme is of the transductor type in which both the biasing features are combined in a single relay and in which the biasing and operating quantities are compared in a static device, i.e. the transductor, and the d.c. electromagnetic relay energised from the transductor is sufficiently robust as to not require repeat-contactors.

The basic elements of a single pole relay are shown in Fig. 15-56. A three limbed core of high-permeability steel has two groups of windings, one on the outer limbs comprising the operating winding and the output winding (which are inductively linked) and the other on the centre limb comprising the bias winding and the smoothing winding (also inductively linked). There is however, no inductive linking between the two groups of windings.

In a simple biased differential scheme of protection, the relay is connected



C.T. LINE AND NEUTRAL CURRENT TRANSFORMERS
A.C.T. AUXILIARY TRANSFORMERS
C.B.T. CORE BALANCE CURRENT TRANSFORMER
E.T. EARTHING TRANSFORMER
E.R. EARTHING RESISTANCE OF IMPEDANCE
E.F. EARTH-FAULT RELAYS (RESTRICTED)
B.R. BIASSED DIFFERENTIAL RELAY.

FIG. 15-55.—*Typical scheme for differential and restricted earth fault protection of a delta/star transformer (Associated Electrical Industries Ltd.).*

as shown in Fig. 15-57. The operating winding is connected across the pilots and is therefore energised by the out-of-balance current, and the bias winding is connected in series with the pilots through an auxiliary transformer and a rectifier and is therefore energised by the circulating current in the pilots.

With external faults, the bias winding is energised by full-wave rectified current of a value dependent upon the magnitude of the fault current. This produces a high saturation throughout the core, the smoothing winding acting to suppress the ripple in the m.m.f. due to the ripple in the bias current. Any out-of-balance currents in the operating winding superimpose an alternating m.m.f. on the bias m.m f. as shown in Fig. 15-58(*a*) but the resulting m.m.f. produces only a relatively small flux change in the core. There is, therefore, only a relatively small output to the relay if the out-of-

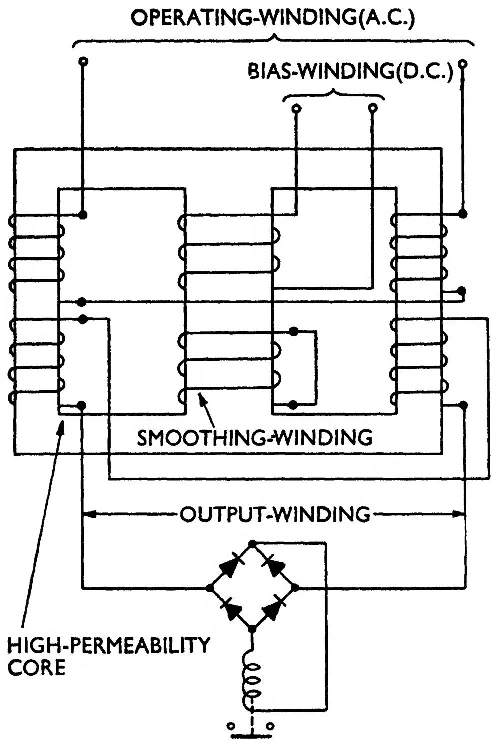


FIG. 15-56.—*Transductor type relay for "Duo-bias" protection (A. Reyrolle & Co., Ltd.).*

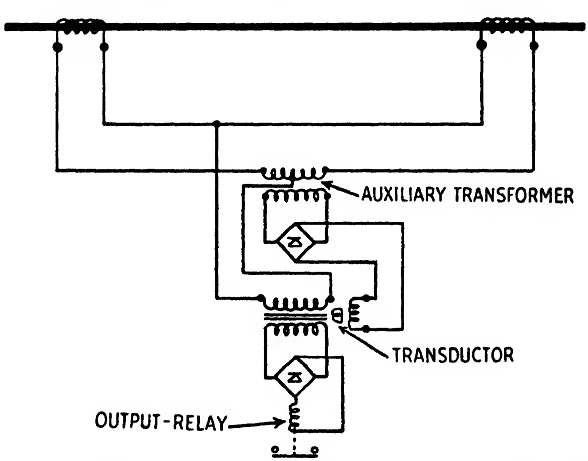
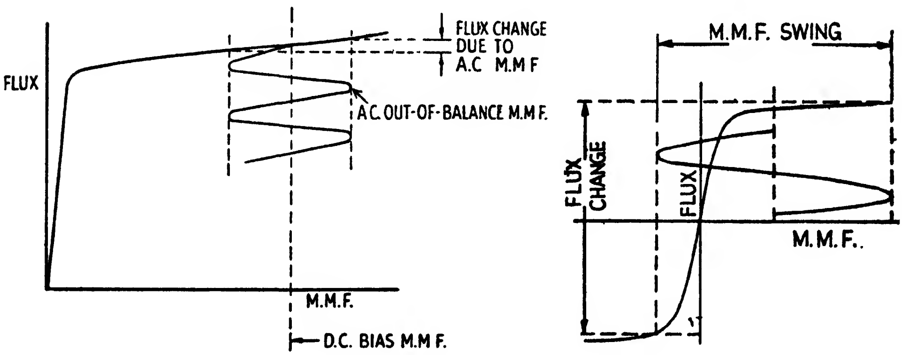


FIG. 15-57.—*Transductor type bias relay used in simple differential protection (A. Reyrolle & Co. Ltd.).*

balance current is less than a certain percentage of the biasing or circulating current.

If an internal fault is fed from one current transformer, only one-half of the bias winding is energised, but the operating winding is energised by the full secondary equivalent of the internal fault current. For these conditions the operating winding m.m.f. greatly exceeds the bias m.m.f. and the resultant flux changes in the core are sufficient to cause operation of the output relay. (See Fig. 15-58(*b*).)



(*a*) (*b*)

FIG. 15-58.—*Fluxes due to operating and biasing ampere-turns "Duo-bias" protection (A. Reyrolle & Co. Ltd.).*

The bias characteristic obtained by such a relay is shown in Fig. 15-59, and is substantially linear.

In practice, a construction involving two separate cores coupled by the bias winding and the smoothing winding is used, this being equivalent in operation to the single core type, but having some practical advantages.

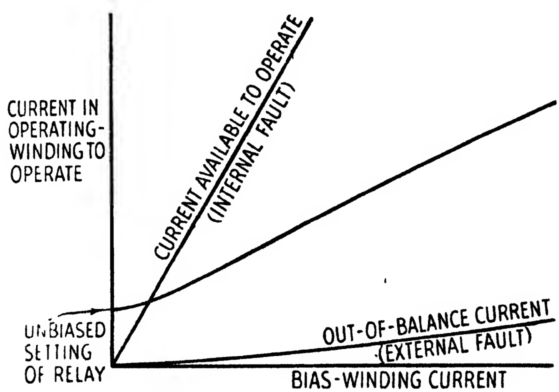
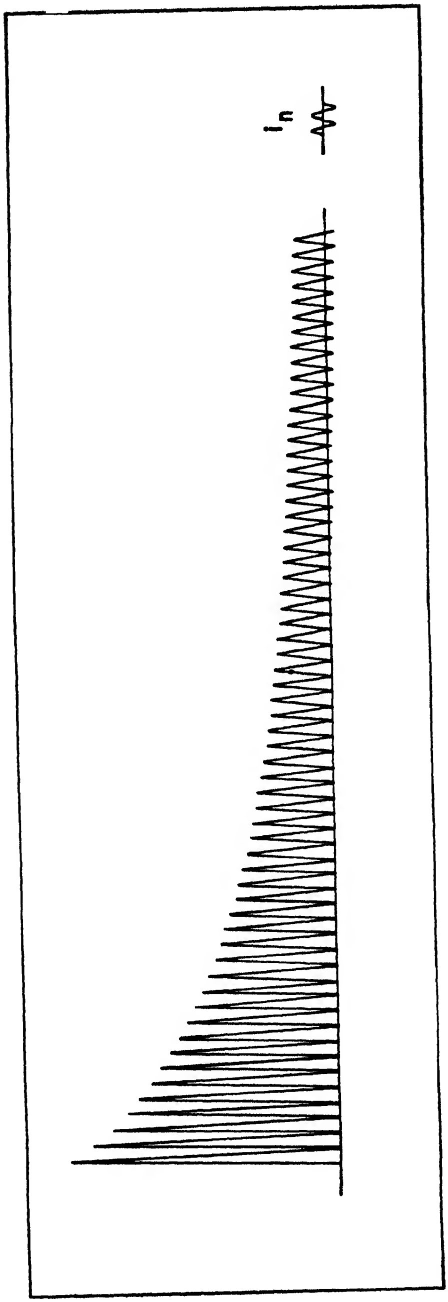


FIG. 15-59.—*Characteristics of transductor type bias relay (A. Reyrolle & Co. Ltd.).*



I_n NORMAL NO-LOAD CURRENT

I_r SWITCHING IN CURRENT RUSH

FIG 15-60 —*Typical wave-form of magnetising current surge when switching in a transformer at the instant V=O.*

A harmonic bias unit (F in Fig. 15-61) comprises a tuned circuit which picks off the second harmonic component of the magnetising surge current in each phase and after rectification and summation, the total bias so obtained is applied to the biasing windings of the transductors.

The wave shape of the magnetising current surge is shown typically in Fig. 15-60. It may be noted that a current-wave of this shape may occur in only two phases of a three phase transformer, the third being energised by a substantially symmetrical transient, not so large as the asymmetrical one but still large compared with the setting of the protective scheme. To ensure stability, the same biasing current is applied to the biasing coils of all three phases connected in series.

Fig. 15-61 shows the "Duo-bias" scheme as applied to a delta/star transformer.

FEEDER PROTECTION

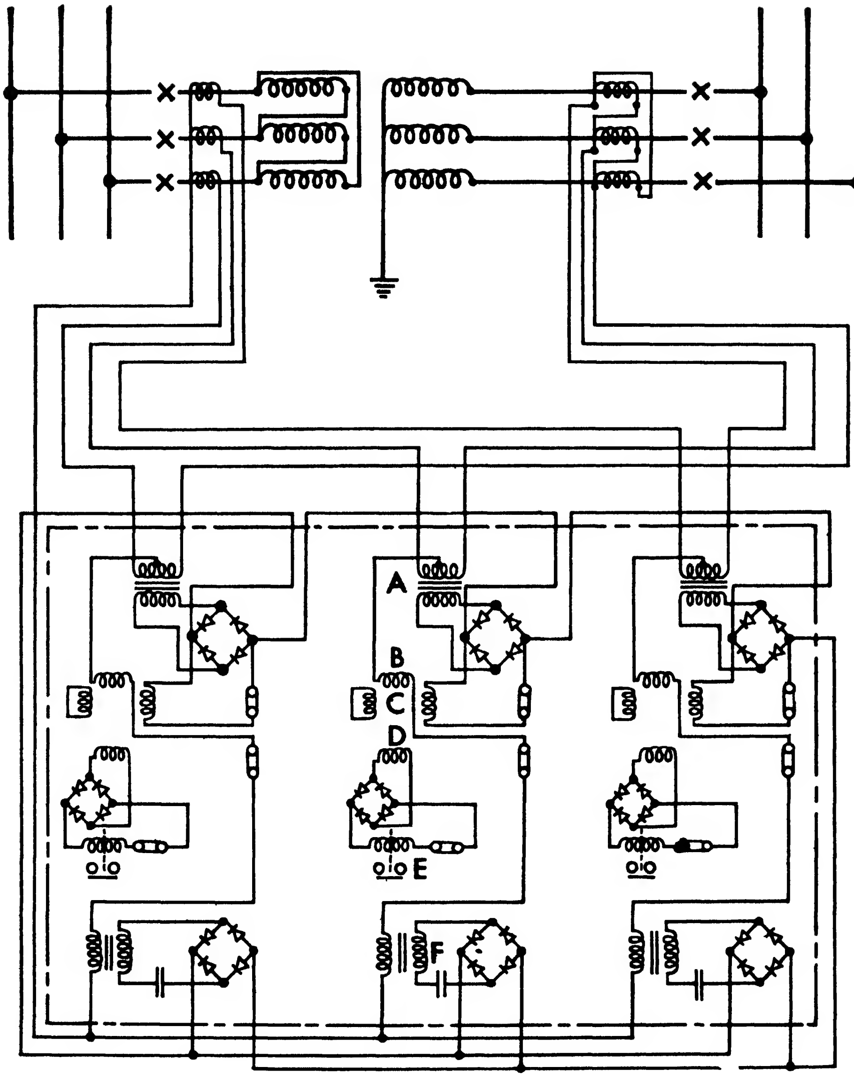
We have shown in our earlier discussion how discriminating overcurrent and earth fault protection can be applied to series, parallel, or ring main feeder circuits by various means depending on circumstances, using time-graded and/or directional or non-directional relays. We have also noted the application of the circulating current system of protection as applied to generator and transformer circuits and, in passing, that this can be applied to feeder circuits subject to the availability of pilot cables running the full length of the cable, often perhaps, for many miles. This means that considerable resistance can exist in the pilots and lead to difficulties with a circulating current scheme. Moreover, with long pilots, many difficulties arise due to capacity currents which tend to flow in the relay circuit unless the pilots are sheathed or special devices are employed to neutralise them.

Because of these problems the system known as "balanced voltage" came into favour in which the relays, located at each end of a feeder, are connected in series through the pilots and so arranged that no current flows in the pilots under normal conditions and, in present-day schemes, with a bias feature to overcome the inherent out-of-balance currents due to pilot capacitance and current transformer inequalities.

Schemes operating on both the circulating current and balanced voltage principles in which the problems enumerated have been taken into account will be described, but because of the many available, and the progress and improvements which are continuously being made, our description will be brief leaving the student or user to study the respective schemes in greater detail from the papers noted in the bibliography or from the named manufacturers's published literature. Space must be found here too to mention schemes which eliminate the need for pilot cables, adding to the need for brevity.

First we may note a circulating current system known as "self-compensated" (Associated Electrical Industries Ltd.), which requires a three core pilot cable.

From the schematic diagram, Fig. 15-62, it will be seen that in addition to the current transformers at each end of the line, a pilot compensator and a vibrating reed relay are used. The compensator comprises a conversion transformer, a resistance and an auto-transformer. The conversion transformer, comprising primary and secondary windings, is so connected that a



A. AUXILIARY TRANSFORMER.
B. OPERATING WINDINGS.
C. BIAS AND SMOOTHING WINDINGS.
D. OUTPUT WINDINGS
E. OUTPUT RELAY
F. HARMONIC BIAS UNIT.

FIG. 15-61.—*Application of "Duo-bias" protection to a delta/star transformer (A. Reyorlle & Co. Ltd.).*

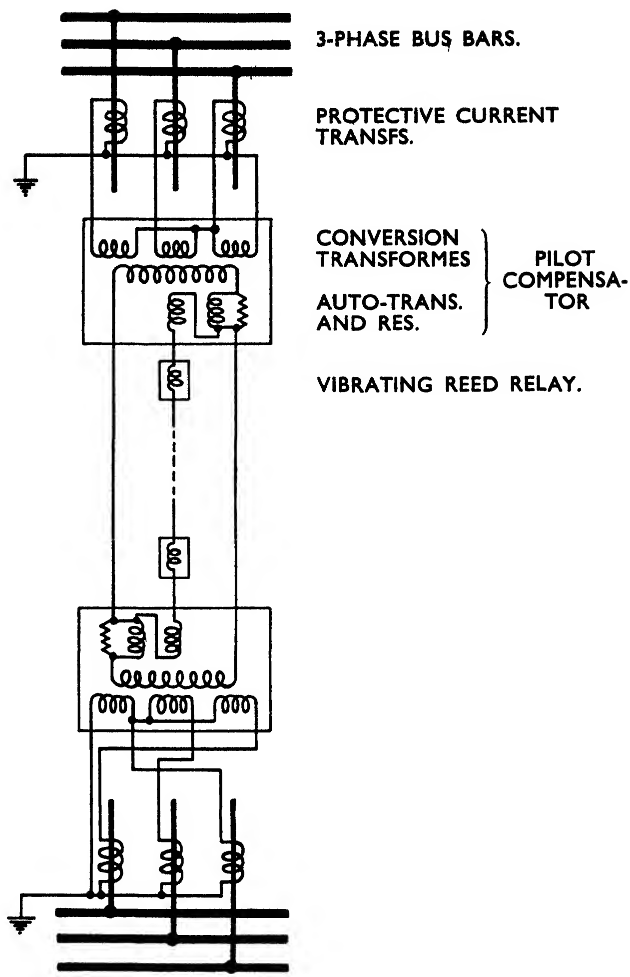


FIG. 15-62.—*Self-compensating feeder protection—Schematic diagram (Associated Electrical Industries Ltd.).*

three phase primary current induces a single phase current in its secondary and it is more sensative to earth-faults than to phase faults. The resistance is adjustable to suit the length of pilot cable, while the auto-transformer has a ratio such that, in conjunction with the resistance, capacity currents in the pilots are eliminated.

The vibrating reed relay operates on the resonance principle and remains undisturbed by any current other than that at a normal system frequency. Thus, transient currents induced in the circuit due to high-frequency disturbances will not cause false operation.

The principle of operation is as follows:—

The single phase current induced in the secondary of the conversion transformer at one end circulates via two outer pilot wires with the single phase current similarly induced at the other end. The relays are connected one at each end of the centre pilot wire between equipotential points. Under healthy conditions (*i.e.* with currents of equal magnitude flowing into and out of the feeder) no current will flow in the centre pilot and the relays will not be energised. When a fault occurs on the protected section the inequality of currents in and out is upset, thus disturbing the balance in the outer pilots and causing a current proportional to the difference between incoming and outgoing primary currents to flow in the centre pilot, and on reaching the setting value, the relays at both ends of the feeder operate to trip out both circuit-breakers. Under normal load conditions, the current circulating in the two outer pilots is of the order of 100 milliamperes and the voltage on the pilots is approximately 10 volts. The latter rises momentarily to approximately 400 volts under maximum through-fault conditions.

Another circulating current scheme is the "Split-pilot" (A. Reyrolle & Co. Ltd.), requiring a three core pilot cable as shown in Figs. 15-63 and 15-64, the former showing the connections where the line current transformers are of the distributed air gap type (D.A.G. for short) and the latter where solid-core transformers are used and in which case the summation current transformer has a distributed air gap.

It may be noted that in the schemes using D.A.G. current transformers, those at the two ends on one phase have the same winding ratio, but those in different phases have different winding ratios. In the scheme using a D.A.G. summation transformer the line current transformers are similar.

Under healthy conditions the current due to the two sets of current transformers in series divides equally between the two parts of the split pilot. Therefore equal currents flow through the two windings of the differentially wound split-pilot transformers, neutralising each other so that no current flows in the relay circuit. The system is therefore stable, because the foregoing holds good no matter what value of current circulates in the pilot system and is thus proof against unwanted tripping due to through faults.

The means provided for tripping when a fault occurs within the protected zone is that of the mid-point tripping connection, made as a plain cross-connection between a common pilot and one core only of the split pilot. This connection is made at middle and equipotential points.

When an internal fault occurs, one set of current transformers such as at "A", Fig. 15-64, will carry a greater current than those at "B", and will generate a greater secondary current. This additional current will be imposed on a still balanced circuit, and will circulate along the left-hand half of the common pilot, across the mid-point connection to the middle point of the split-core, to which it is connected. From this point the additional current flows back to the left-hand junction of the split-pilot by two parallel paths—one, the short path represented by the left-hand end of split-pilot 3, and the other (a long path) represented by the right-hand end of split-pilot 3 and the whole length of split-pilot 2. The ratio of these lengths is clearly 1:3, three-quarters of the additional (tripping) current flowing in the short path and one quarter in the long path.

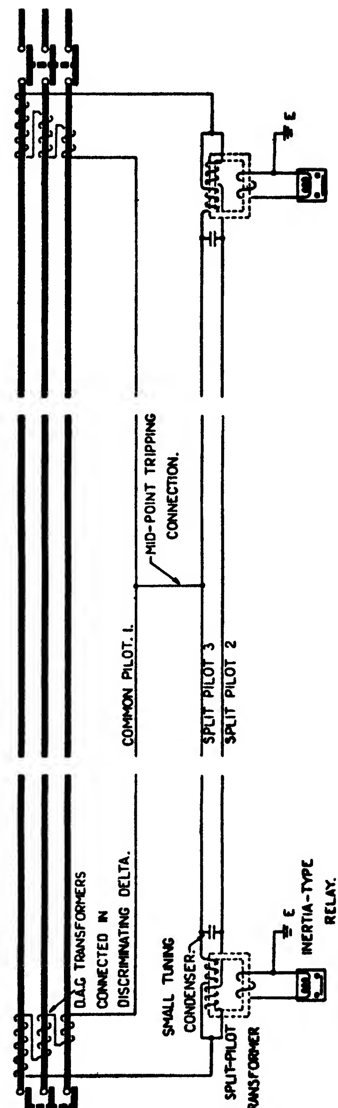


FIG. 15-63.—*Split-pilot feeder protection (A. Reyrolle & Co. Ltd.).*

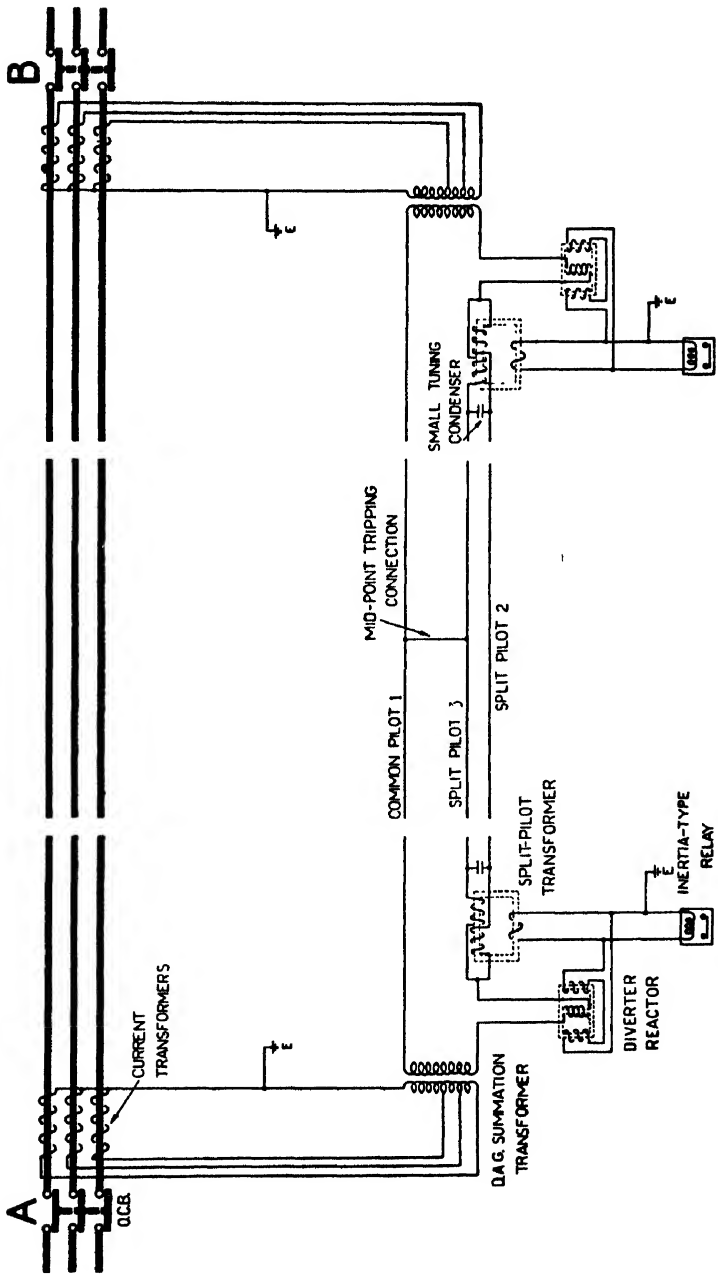


FIG. 15-64.—*Split-pilot feeder protection (A. Reyrolle & Co. Ltd.).*

In the differential windings of the split-pilot transformer at end "A" one winding carries three-quarters of the tripping current and the other one-quarter, both currents being in the same direction, giving a combined effect equal to one-half the tripping current. In the split-pilot transformer at end "B" each winding carries one-quarter of the tripping current, but in opposite directions, the combined effect being equal to one-half.

Thus, the difference current due to a fault is divided to provide equal tripping energy at each end. In the case where a D.A.G. summation transformer is used, it is necessary to include a diverter reactor, the purpose of which is to compensate for the unbalance due to the use of solid-core current transformers.

A well-known scheme of feeder protection is that known by the name "Translay" (Associated Electrical Industries Ltd.) and requiring only two pilot wires for a three phase feeder.

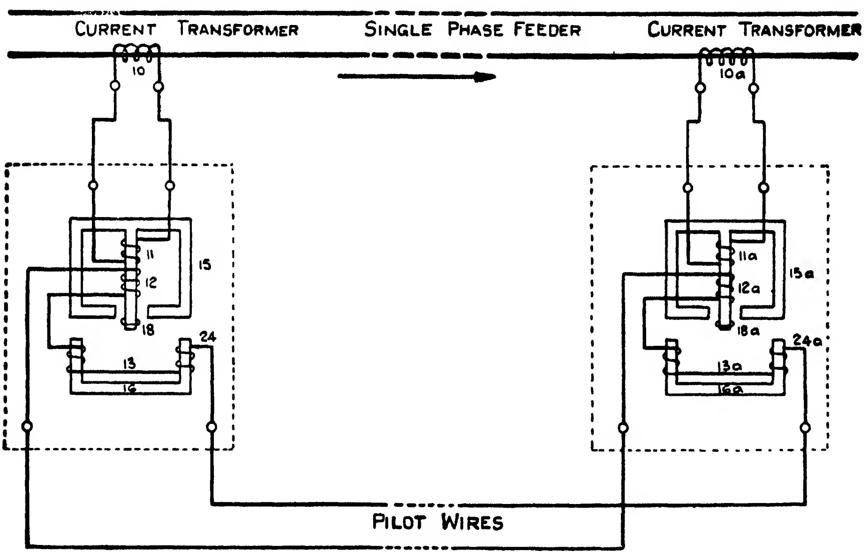


FIG. 15-65.—*Simplified diagram of "Translay" feeder protection (Associated Electrical Industries Ltd.).*

The name "Translay" is evolved from the fact that the relay embodies a transformer feature. It provides complete protection against both earth and phase faults and can be applied to single or three phase feeders, transformer feeders, feeders with a tee-off and parallel feeders. It is based on the established principle of the current entering at one end of a feeder being equal at any instant to that leaving at the other.

In its simplest form, operation of this system can be followed by reference to the simplified diagram, Fig. 15-65, for a single phase feeder. It should be noted that for the sake of clarity, tripping circuits have been omitted.

Under healthy conditions, current transformers 10 and 10a carry equal currents, and the coils, 11 and 11a, induce equal e.m.f.'s in the windings,

12 and 12a. These latter windings are in opposition via the pilot wires with the operating windings, 13 and 13a, in series with them. Thus no forward torque is exerted on the disc. On the occurrence of a fault, the current through one transformer is greater than that through the other. A small current circulates through the operating windings and pilots, and when it reaches the set value causes the relay to close the tripping circuit and to disconnect the feedbar.

This system, which is usually employed on a three phase circuit, has a single-element relay (type HO2) at each end of a feeder which gives protection against both faults between phases and faults to earth. The connections are those shown in Fig. 15-66, in which, for the sake of clarity, the tripping circuits are omitted. The action under fault conditions is as follows:—

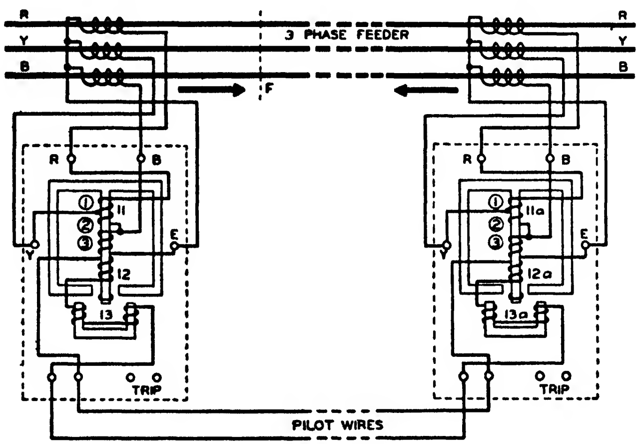


FIG. 15-66.—"*Translay*" *protection applied to three phase feeder (Associated Electrical Industries Ltd.).*

Assuming a fault, F, between phases R and Y, fed in the direction of the arrows, the currents that flow in sections (1) of the relay primary windings, 11 and 11a, induce e.m.f.'s in windings 12 and 12a which, being now additive, cause a current to circulate in the operating coils, 13 and 13a, and the two pilot wires. Both the upper and lower electromagnets thus become energised and, if the fault current exceeds the value corresponding to the scale setting in use, the relays operate to trip their associated circuit-breakers. A fault between Y and B phases causes sections (2) of windings 11 and 11a to be energised and the relays to operate, while a fault between R and B phases causes operation by energising sections (1) and (2) of windings 11 and 11a, the fault setting in this case being one-half of that for the R-Y and Y-B cases.

In the event of an earth-fault on phase R, the resultant secondary current from the current transformer in phase R flows through the sections (1), (2) and (3) of windings 11 and 11a—assuming power flow to be in the

directions indicated by the arrows. As the e.m.f.'s induced in windings 12 and 12a are now additive, a current will circulate in the operating windings, 13 and 13a, by way of the two pilots, thereby causing operation of the relays. The fault setting will be approximately one-half of that represented by the scale setting which is based on a fault on phase B, for which only sections (3) are energised. In the case of an earth-fault on phase Y, current will flow only in sections (2) and (3) on windings 11 and 11a, and the fault setting will now be approximately two-thirds of that represented by the scale setting.

This form of protection can be applied to tee'd feeders (where the current entering is balanced against that leaving by two sources), to transformer feeders (where transformer and feeder are switched as a unit without intervening circuit-breaker), and to parallel feeders (where a Translay element is combined with a directional element). The relays used for these schemes differ slightly.

A balanced voltage scheme known as "Solkor-A" (A. Reyrolle & Co. Ltd.) employs a two core pilot cable, and ordinary solid core (hence the name "Solkor") current transformers. Among its features are the use of saturable auxiliary current transformers and a tuned relay circuit.

The effect of the saturable summation transformers is to distort the pilot voltage wave-form under heavy through-fault conditions so that the difference between the output voltages of the two "Solkor" boxes at opposite ends of a feeder, due, for example, to dissimilarity of the current transformers at the two ends, is largely composed of higher harmonics. It follows that the out-of-balance current flowing in the pilot circuit is also composed of higher harmonics and so cannot cause wrong operation, since the relay circuits are tuned for 50 cycles. This tuning also makes the relays immune from operation by the high-frequency currents that could be set up by transients in the main cable.

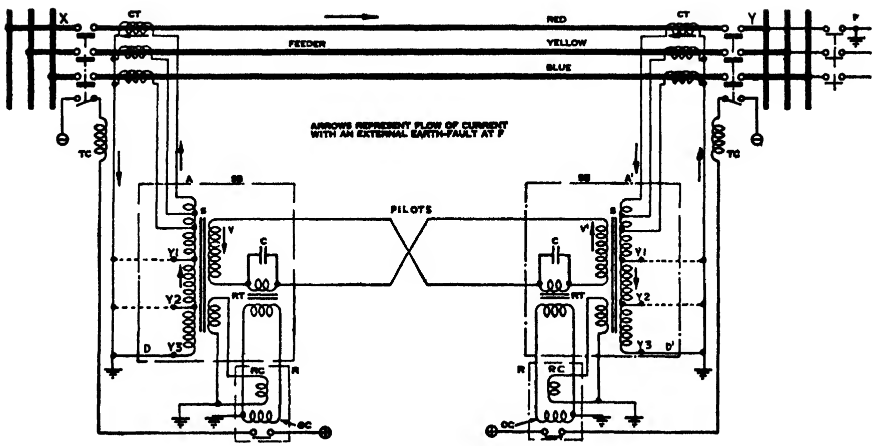
The saturable summation transformers also limit the pilot voltage and thus limit the 50 cycle pilot capacity current which is a common source of unbalance in voltage balance systems.

Stability is still further improved by the use of restraining coils in the relays, these virtually increasing the relay settings with increase of through fault current.

The way in which the main current transformers are connected to the summation transformers ensures response to both internal earth-faults and phase faults, and the tappings of the summation transformers are so arranged that the sensitivity to earth-faults is greater than to phase faults.

The connections of the "Solkor" plain feeder protective system are illustrated in Fig. 15-67. The three current transformers at each end of the feeder are connected to tappings on the primary windings of the summation transformer, the secondary winding of which is in series with the pilots. A single pole rotating-armature electromagnetic relay is provided at each end of the feeder and its operating coil is energised from the secondary winding of a relay transformer, the primary winding of which is in series with the pilots. The operating-coil circuit is tuned by means of a condenser connected across the primary winding of the relay transformer, so that the relay responds to currents only at or near the fundamental frequency.

The restraining coil is connected to a tertiary winding on the summation



C. TUNING CONDENSER
O.C. OPERATING COIL
R. RELAY.
R.C. RESTRAINING COIL
R.T. RELAY TRANSFORMER
S. SUMMATION TRANSFORMER
S.B. "SOLKOR" BOX
T.C. TRIP COIL

FIG. 15-67.—*"Solkor-A" protection applied to a three phase feeder (A. Reyrolle & Co. Ltd.).*

transformer and carries a current that increases with the primary current.

Due to the interposing of the relay transformer, the relay is electrically separated from the pilots and therefore any high voltage induced in the pilots (for example, by earth-fault currents in the lead sheath of the pilot cable) does not appear in the relay, and the relay, therefore, is always safe to work on.

The operation of this protective scheme with internal and external faults is as follows, reference being made to Fig. 15-67:—

On the occurrence of an external earth-fault in the red phase, current flows out of the red phase current transformer secondary at the end X into the primary winding of the summation transformer at D, through the whole winding, out at A, and back to the current transformer. This produces a voltage in the secondary winding as shown by the arrow V. At the end Y an identical current flows into the summation transformer at A^1 and out at D^1, producing the secondary voltage, V^1.

The two secondary voltages, V and V^1, are substantially equal in magnitude, both being produced by the same primary current but are in opposition. The effect on the relays of any small pilot current (due, for example, to difference in the characteristics of the current transformers and to pilot capacity current) is made negligible by the means already described.

With an internal fault fed from one end of the feeder, one summation transformer is energised, and current circulates in the pilots because there is no opposing voltage at the other end. The pilot current traverses the primary windings of the relay transformers, which are in series with the pilots and a current is therefore produced in the relay transformer secondaries which are connected to the operating coils of the relays. Operation takes place at both ends. If an internal fault is fed from both ends of the feeder, the two primary currents are in opposite directions and the resultant secondary voltages assist each other in circulating the pilot current. In systems in which the earth-fault current is necessarily small compared with the load current of the protected feeder, tappings on the summation transformer enable very sensitive earth-fault settings to be obtained.

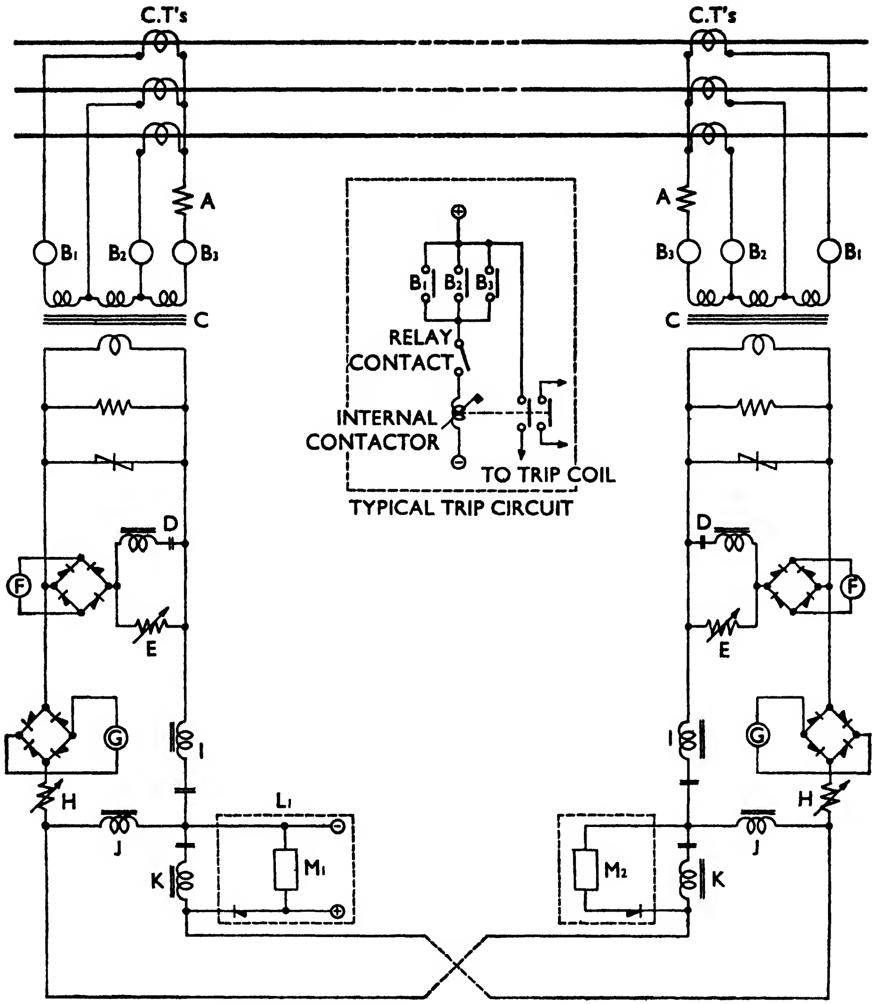
This type of protection can be applied also to a tee'd feeder and to a feeder transformer unit where a high-voltage feeder is directly connected to the terminals of a power transformer, the combination being controlled by only one circuit-breaker at each end.

The "Solkor-A" scheme as depicted in Fig. 15-67 allows for the ideal arrangement where the "Solkor" boxes (S B) can be mounted on or near the switchgear and the relays (R) can be separately mounted on remote relay panels. The design of the switchgear however may be such as to restrict the space available for the "Solkor" box while ample room may be available at the relay panel. To meet such a condition, a scheme known as "Solkor-B" has been developed in which the whole of the equipment is contained within the relay case.

In principle this scheme functions as described earlier, but the relay transformer has been dispensed with and the relay coil is connected directly in the pilot circuit.

When discussing protective gear for transformer protection, we noted some brief details of the "Stabilay" relay and its use in a biased differential scheme of protection. Relays of the same pattern have been employed in a high-speed pilot wire biased differential scheme for feeder protection (Associated Electrical Industries Ltd.). It is of the balanced-voltage type and is designed for use with rented telephone type pilots. Fig. 15-68 is a simplified schematic diagram from which it is seen that resistance-loaded current transformers at each end of the feeder are connected through pilot wires and relay operating coils at each end to form a balanced-voltage circuit. Under normal load or through-fault conditions the current transformer outputs at the two ends balance each other and no current will flow in the relay operating coils. Under internal fault conditions, this balance is upset and current will flow causing the relays to operate and trip their associated circuit-breakers. The relay is fitted with a second coil, a restraint coil. Under through-fault conditions, when a relatively high voltage is established across the pilots, each relay will be influenced by a restraining force large enough to allow a considerable degree of unbalance in the balanced-voltage circuit.

A three-element instantaneous two pole overcurrent and single pole earth-fault relay is included in the circuit, energised directly from the line current transformers. These relays have normally open contacts on each element and these are paralleled and connected in the tripping circuit of the differential relay, as shown inset in Fig. 15-68 at B1, B2 and B3.



A. STABILISING RELAY.
B_1, B_2, B_3 CHECK RELAY (OVERCURRENT AND EARTH-FAULT)
C. SUMMATION CURRENT TRANSFORMER
D. SERIES TUNED ACCEPTOR CIRCUIT.
E. BIAS RESISTOR (IN BIASSED DIFFERENTIAL RELAY)
F. RESTRAINT COIL (IN BIASSED DIFFERENTIAL RELAY)
G. OPERATING COIL (IN BIASSED DIFFERENTIAL RELAY)
H. PILOT PADDING RESISTOR (IF REQUIRED)
I, K. SERIES TUNING CIRCUIT
J. PILOT TUNING CHOKE
L_1 PILOT SUPERVISION—D.C SUPPLY UNIT
M_1, M_2 PILOT SUPERVISION RELAY

FIG. 15-68.—*Simplified schematic diagram of biased differential feeder protection with "Stabilay" relay (Associated Electrical Industries Ltd.).*

This relay is described as a check relay and, is used to eliminate false tripping should a defect appear on the pilots. This condition is detected by a system of continuous pilot supervision and the check relays prevent tripping due to the load current, which may otherwise occur with a faulty power circuit. The differential relay has a low setting, but the effective setting will be that of the check relay, varying from 100 to 200% for phase faults and 40-80% for earth-faults. Pilot supervision is injected at one end whilst pilot failure is detected by a polarised relay at the opposite end.

The scheme provides that when an internal fault is fed from one end only the relays at the feeding end will operate to open the associated breaker. If the feeder is fed from both ends, as in parallel feeder or ring main systems, the relays and circuit-breakers at both ends will operate and trip to completely isolate the feeder.

Magnetising inrush currents produced when a transformer is energised (see earlier discussion) flow through the surrounding transmission network and may cause the protective gear to operate due to the pronounced harmonics. The principle of harmonic restraint noted in the earlier discussion is applied in this form of feeder protection, using a tuned circuit shown at I and K in Fig. 15-68.

When applying a scheme of this type to telephone type pilots some means of limiting the maximum voltage developed across the pilots is is essential. A non-linear (Metrosil) resistor connected across the secondary terminals of the summation transformer limits the voltage across the pilots to 130 volts peak. The choke J connected across the pilot wires tunes out the effect of pilot capacitance and completes the pilot supervisory circuit. An appreciation of the high-speed characteristics of this form of protective gear is obtained by noting that with a single infeed, the total operating time is of the order of five cycles (0·10 seconds) for currents up to five times the setting falling to three cycles (0·06 seconds) at maximum fault values.

Another scheme operating on the balanced or opposed voltage principle requiring a two core pilot cable of the telephone type or conventional twin cable is the "Zedpilot" scheme developed by The General Electric Co. Ltd. In this, an internal fault, i.e. a fault at any point between the opposing groups of current transformers located at each end of the feeder, causes *both* feeder end circuit-breakers to be tripped open regardless of whether the fault is fed from one end or from both.

As in other balanced voltage schemes, no current flows in the pilots and relay operating coils so long as the current in the primary line is equal in magnitude and compares in phase as between the entering and leaving ends.

Fig. 15-69 is a schematic diagram of the system from which it will be seen that the three current transformers (of normal design) at each end of the feeder are connected to a summation transformer of the air gap type. The function of this summation transformer is to convert a three phase current input into a single phase voltage output and serve incidentally to isolate the pilots from the main current. transformers. A non-linear resistor connected across the secondary terminals of the summation transformer effectively limits the voltage which can appear on the pilots to less than 300 volts peak. The relay used is a sensitive polarised unit employing a moving-coil movement for d.c. operation. Biasing (to obtain stability with heavy through-faults and current transformer inequalities) is obtained

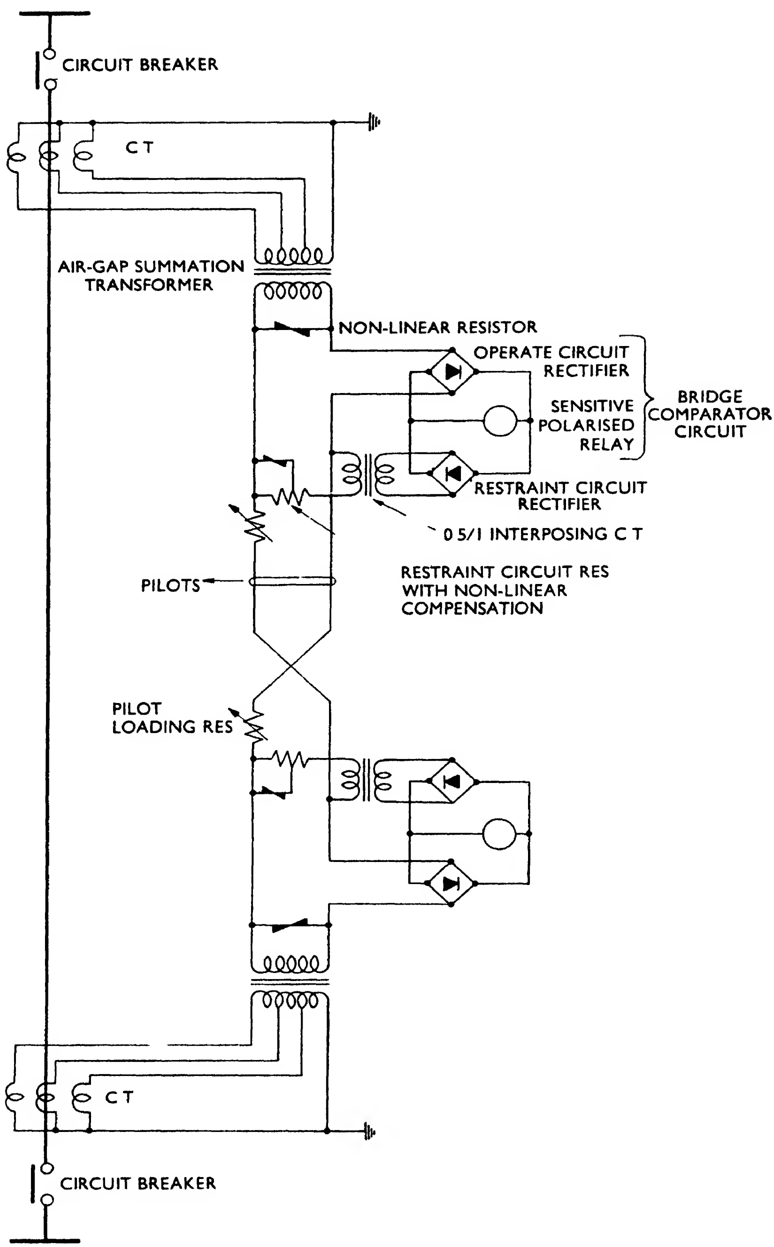
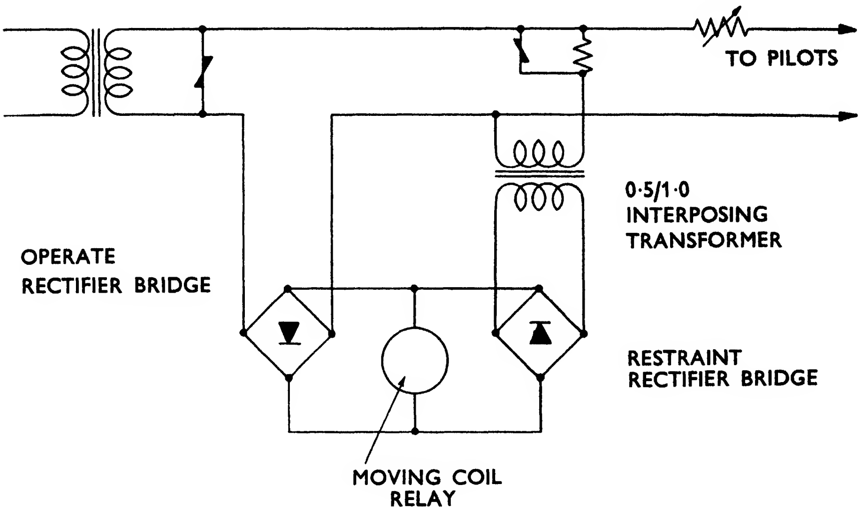


FIG. 15-69.—*Schematic diagram of "Zedpilot" feeder protective system (The General Electric Co. Ltd.).*

in this scheme by employing a rectifier bridge comparator circuit as shown in Fig. 15-70. In this arrangement the two a.c. operate and restraint



WHEN THE OPERATE RECTIFIER CURRENT OUTPUT EXCEEDS THE RESTRAINT OUTPUT, CURRENT FLOWS THROUGH THE RELAY IN THE DIRECTION TO CAUSE OPERATION.

FIG. 15-70.—*Biasing by rectifier bridge comparator (The General Electric Co. Ltd.).*

current inputs are rectified and flow in what is essentially a differential current circuit. The relay element is connected across the two rectifiers and if the operate current exceeds the restraint current input, current will flow through the polarised relay in the direction to cause operation. If, on the other hand, the restraint current input predominates, the current flowing through the relay is in the reverse direction and the relay movement is held against operation.

An interesting feature of the "Zedpilot" scheme is that the relays may be used as intertrip devices, the application of a d.c. voltage to the pilots at one end causing the relay at the opposite end to operate and trip out the remote circuit-breaker.

Thus the circuit-breaker at an attended end of a feeder may be opened by hand trip and the same operator can completely isolate the feeder by opening the remote circuit-breaker.

The high speed of operation achieved by this scheme is indicated by the following:—

100 milliseconds with faults of three times the just operate level
50 milliseconds with faults of 10 times the just operate level.

The increasing use of lightly insulated cables for communication circuits, remote control and telemetering has suggested the use of the same or similar cables for protection. These cables are, as a rule, privately owned

and therefore the terminal equipment is not subject to the stringent requirements imposed when national communication pilots are used.

The Reyrolle "Solkor-R" protection has been specifically designed to meet these pilot cable conditions, i.e. relatively low insulation, relatively high core resistance, and privately owned, but its use is not in any way restricted to these conditions and it can be applied equally well to any feeder using any ordinary kind of privately owned pilot cable.

The basic protective circuit is that shown in Fig. 15-71. As we have noted in our general discussion on the circulating current principle, the protective relay operating coils are connected in shunt with the pilots across points which have the same potential when current circulates round the loop. In this scheme, equipotential relaying points during *external* faults

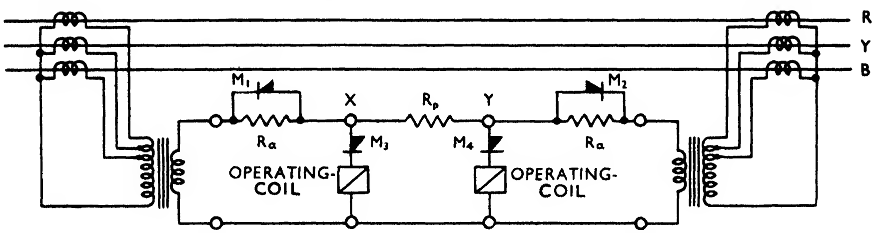


FIG. 15-71.—*Basic circuit of "Solkor-R" high-speed feeder protection. (A. Reyrolle & Co. Ltd.).*

exist at one end during one half-cycle of fault current and at the other end during the next half-cycle. During the half-cycles when the relay at either end is not at the electrical mid-point of the pilot system, the voltage appearing across the relay is in the reverse direction to that required for operation.

At each feeder end, the secondaries of the line current transformers are connected to the primary of a summation transformer. For various types of current distribution in the three current transformers, a single phase quantity appears in the summation transformer secondary and is applied to the pilot circuit. Thus the comparison of currents entering and leaving the feeder is on a single phase basis. In the basic diagram, the resistance of the pilot cable is represented by Rp, the rest of the loop comprising the resistors Ra and the rectifiers M1 and M2. The operating elements which are made unidirectional by rectifiers M3 and M4, are connected in shunt with the pilots at points X and Y.

When a fault occurs external to the protected zone, an alternating current circulates around the pilot loop. On alternate half-cycles one or other of the resistors Ra at the two ends of the pilot is short-circuited by its associated rectifier M1 or M2, and the total resistance in the pilot loop at any instant is, therefore substantially constant and equal to Ra+Rp. The effective position of Ra, however, alternates between the two ends being dependent on the direction of current. This change in position of Ra makes the voltage distribution between the pilot cores different for successive half-cycles of the pilot current, the effective circuits on successive half-cycles being shown in Fig. 15-72 at (*a*) and (*b*).

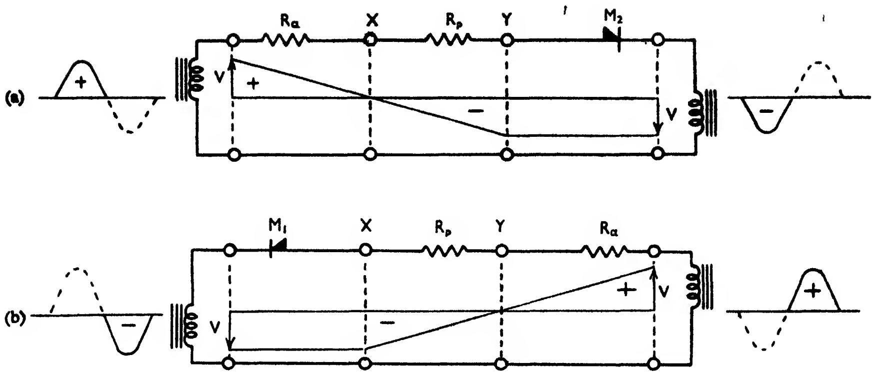


FIG. 15-72.—*Behaviour of basic circuit under external fault conditions. (a) and (b) show effective circuits during alternate half-cycles (A. Reyrolle & Co. Ltd.).*

These diagrams indicate also the resulting potential-gradient between pilot cores when Ra is equal to Rp and it will be seen that the voltage across the relays at points X and Y is either zero (because the relay is at an electrical mid-point) or in the reverse direction for conduction of current through rectifier M3. Therefore, when Ra=Rp, a reverse voltage appears across the relay circuit during one half-cycle and zero voltage during the next. The voltage across each relaying point X and Y during a complete cycle is shown in Fig. 15-73 at (a).

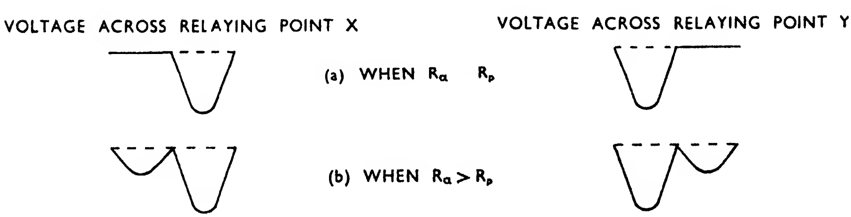


FIG. 15-73.—*Voltage across relaying points X and Y during one cycle of external fault current (A. Reyrolle & Co. Ltd.).*

In practice, resistors Ra are made greater than the pilot loop resistance Rp and this causes the point of zero potential to occur within resistors Ra as shown in Fig. 15-74, and the voltage across X and Y throughout a complete cycle is now that shown at (b) in Fig. 15-73.

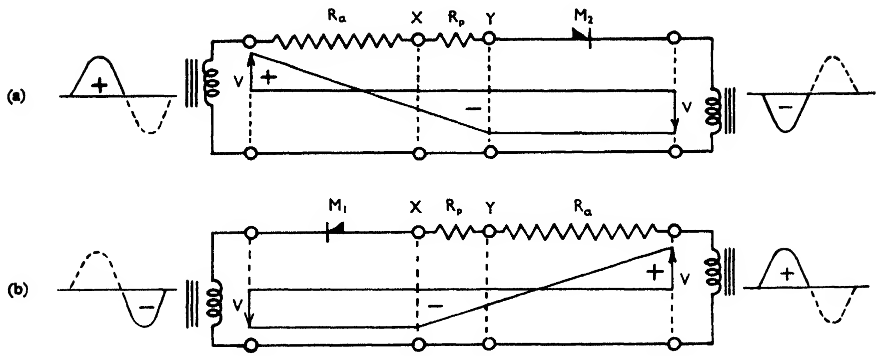


Fig. 15-74.—*Behaviour of basic circuit under external fault conditions when Ra is greater than Rp. (a) and (b) show effective circuits during alternate half-cycles (A. Reyrolle & Co. Ltd.).*

Thus, instead of having zero voltage across each relay on alternate half-cycles, there is on both half-cycles a voltage in the reverse direction to that required for operation and as this voltage must be overcome before operation can take place the effect is to enhance the stability on through faults.

When a fault occurs *within* the protected zone and with current fed equally from both ends, the effective circuits during successive half-cycles are those shown at (a) and (b) in Fig. 15-75. From this it is seen that

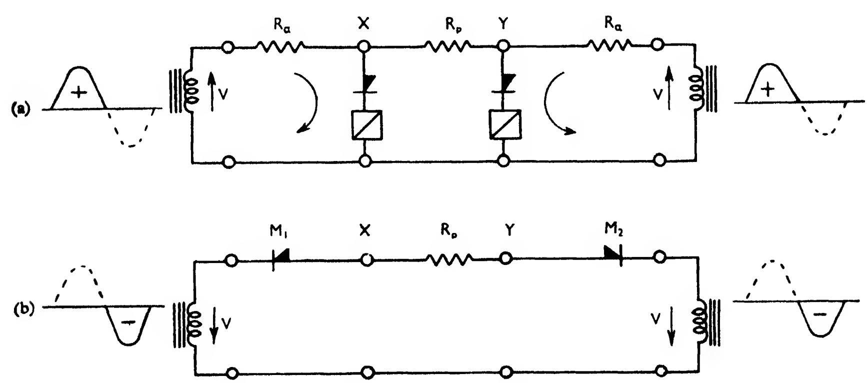


Fig. 15-75.—*Behaviour of basic circuit under internal fault conditions fed from both ends. (a) and (b) show the effective circuits during alternate half-cycles (A. Reyrolle & Co. Ltd.).*

pulses of current pass through each relay on alternate half-cycles and the relays at both ends will operate. If the current is fed from one end only, the relay at the remote end (in series with the pilot loop resistance Rp) is energised in shunt with the relay at the feeding end. The relay at the feeding end operates at the setting current and the relay at the remote end at approximately 2·5 times the setting current. Providing therefore, that the fault current is not less than 2·5 times the fault setting, the relays at both ends operate to completely isolate the circuit.

Fig. 15-76 is a schematic diagram of the complete protective system.

All schemes of differential protection for feeders so far described have required the use of pilot cables. When a feeder is of any length this can be

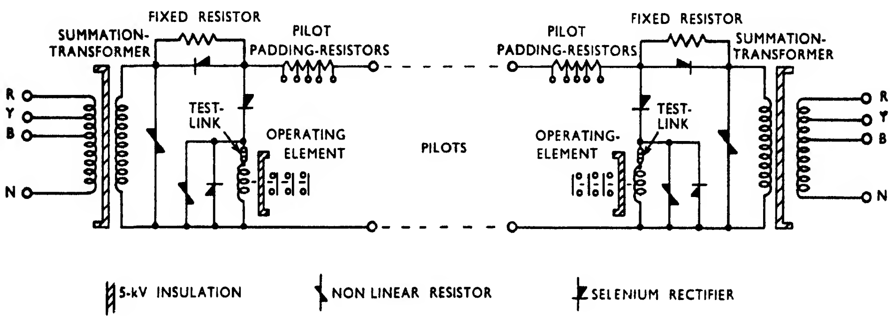


FIG. 15-76.—*Schematic diagram of complete "Solkor-R" protective system (A. Reyrolle & Co. Ltd.).*

costly and is rarely economical when the line is greater than 15 to 20 miles in length.

It is natural, therefore, that a scheme or schemes should be sought in which discriminating protection is obtained without the use of pilot cables and two such schemes which have been available for a number of years are those known as "Distance" (or "Impedance") and "Carrier Current". The complexity of the modern versions of both are such as to make it impossible to give other than a brief indication of the basic principles.

The basic principle of distance protection is that the distance between any point in the power system and a fault is proportional to the ratio of voltage to current (V/I), i.e. the impedance (Z) between the two points. The protection, therefore, provides time grading in accordance with the line impedance, the operating time increasing with distance from the fault. If, for example, in Fig. 15-77 we assume a fault at F, then it is clear that the circuit-breaker associated with relay R1 should be the one to open and clear the fault, leaving the breakers at R2 and R3 closed. The simple sketch Fig. 15-77 shows that this will be so because the ratio V/I at this point will be lower than at relays R2 and R3.

In this form of protection, the increase in operating time is in steps and a typical distance/time characteristic for the Reyrolle "Selecta-Mho" type of protection is shown in Fig. 15-78.

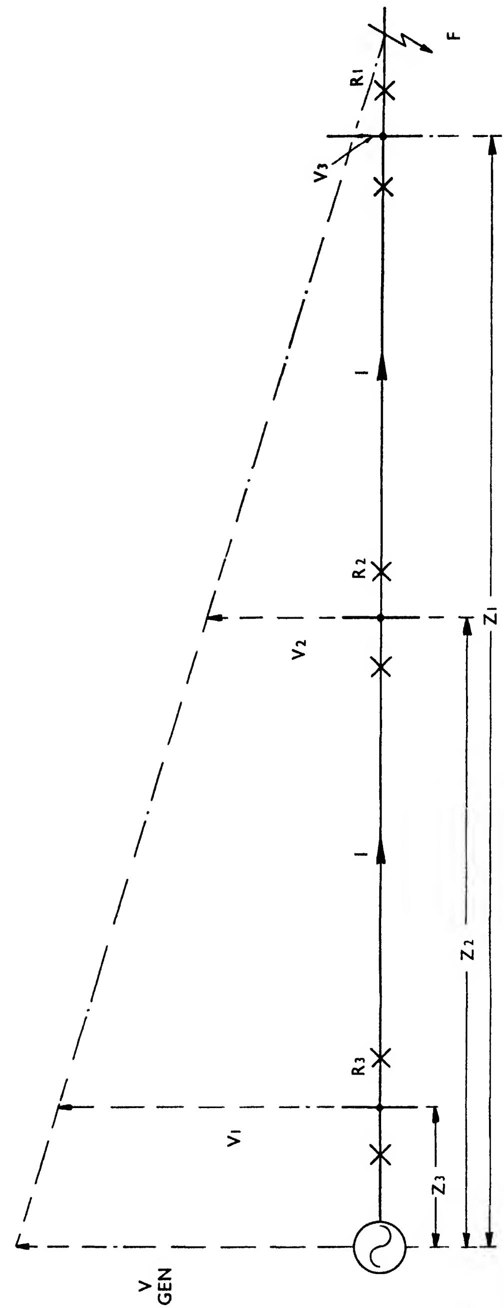


FIG. 15·77.—*Simplified basic principle of distance protection.*

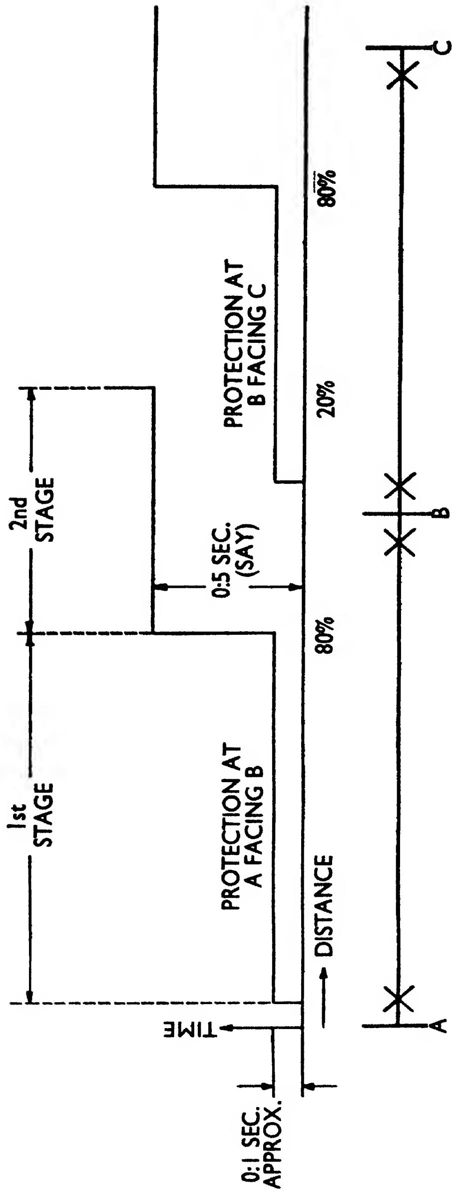


FIG. 15-78.—*Distance/Time characteristic of "Selecta-Mho" protection.* (A. Reyrolle & Co. Ltd.).

From this, starting at A, it will be seen that there is, to all intents and purposes, an instantaneous operating zone covering 80 per cent of the feeder A-B. This is followed by a time-lag zone covering the remainder of this feeder and a portion of the series feeder B-C. A third stage of non-directional definite time lag overcurrent protection follows for the remainder for back up protection.

The "Selecta-mho" scheme uses a single distance element of the polarised mho (directional impedance) type. The protection is started by three instantaneous overcurrent elements which select the current and voltage supplied to the mho element according to the type of fault. In order that the overcurrent relays may always make this selection correctly, their current setting must always be higher than the full-load current of the feeder and this presupposes that the available fault current must also be higher than full-load. This is not always the case in networks above 33 kV.

As previously mentioned, the distance measuring relay is of the directional impedance type having a mho type characteristic, which means that it operates if the line impedance from the relay point to the fault is less than a predetermined value when the fault power flows in a given direction.

For higher voltage lines and/or where system conditions are such that fault currents may be less than normal full-load current, the same Company have available another scheme known as "Type H High Speed Impedance" protection. This scheme employs separate distance measuring elements of the polarised mho type for each type of fault, with separate offset impedance elements for starting.

In a scheme of carrier-current protection known as "Telephase", developed jointly by A. Reyrolle and Co., and The General Electric Co. Ltd., the circulating current principle of comparing the magnitudes and phase angles of the currents at the two ends of a protected circuit is modified in that when the fault current setting is reached or exceeded, the comparison is made only between the phase-angles of the currents at the two ends of the protected circuit. Simultaneous measurement of such phase displacement at both ends is made possible by means of a high-frequency carrier link, the carrier signals being transmitted to the main power lines from both ends. This involves, as the block diagram Fig. 15-79 shows, transmitting and receiving fault detection and high-frequency line-coupling equipment at both ends of the line.

BUSBAR PROTECTION

The types of protection so far discussed have been concerned with the protection of the section of the electrical network with which they are associated, i.e. generators, transformers and feeders. This is shown in diagrammatic form in Fig. 15-80, from which it will be noted that at any switchboard there may be a most vital section without protection against possible faults—a section known as the busbar zone.

This zone may be regarded as being so important that it must be kept free from damage, and it is to this end that busbar zone protective schemes have been introduced. Whether such protection is provided or not depends on whether the position in the network and the main switchgear at key power stations are of sufficient importance to warrant the additional expenditure involved.

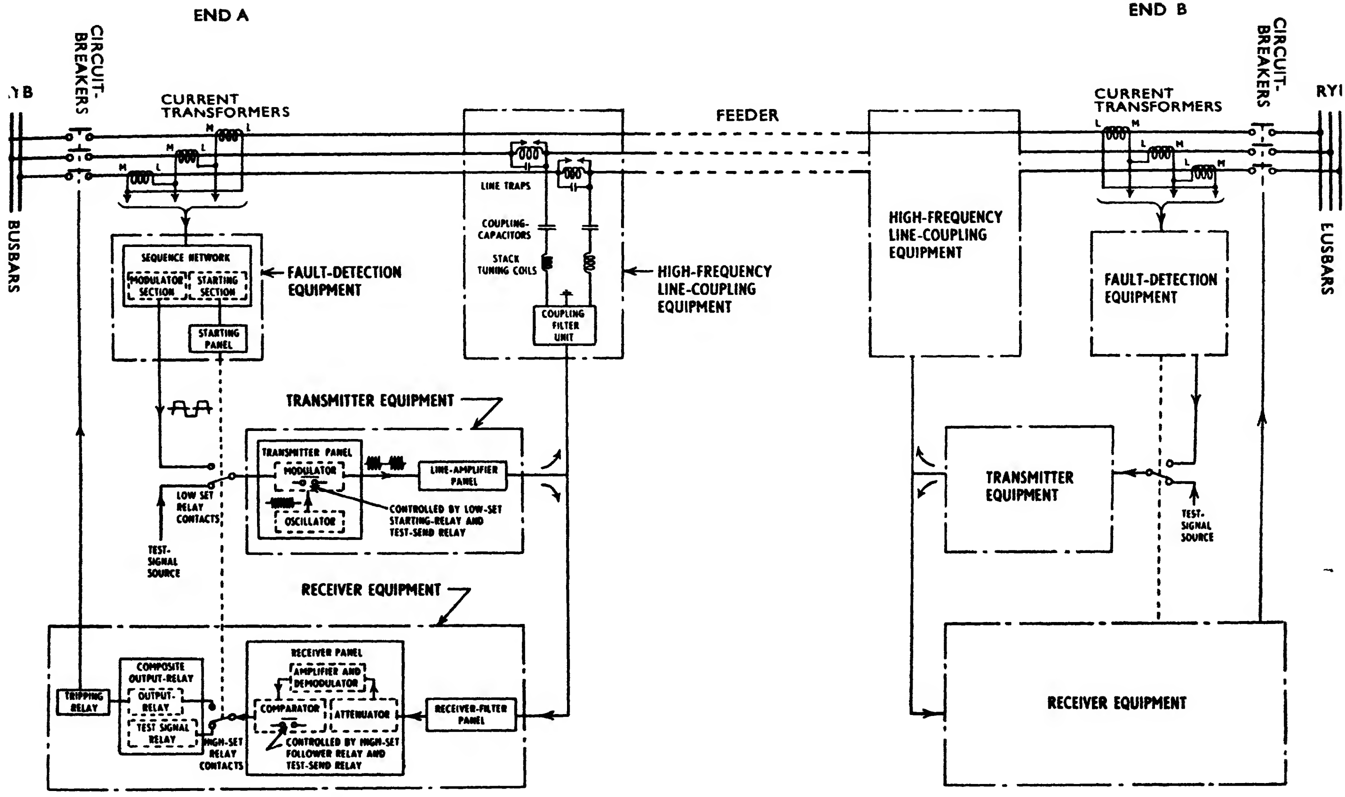


FIG. 15-79.—*Block diagram showing method of connection of "Telephase" protection using phase/phase line coupling. (A. Reyrolle & Co. and The General Electric Co. Ltd.).*

In some instances, back-up overcurrent protection on generators or transformers will give some degree of busbar protection, but only after a relatively long time in which considerable damage may be done.

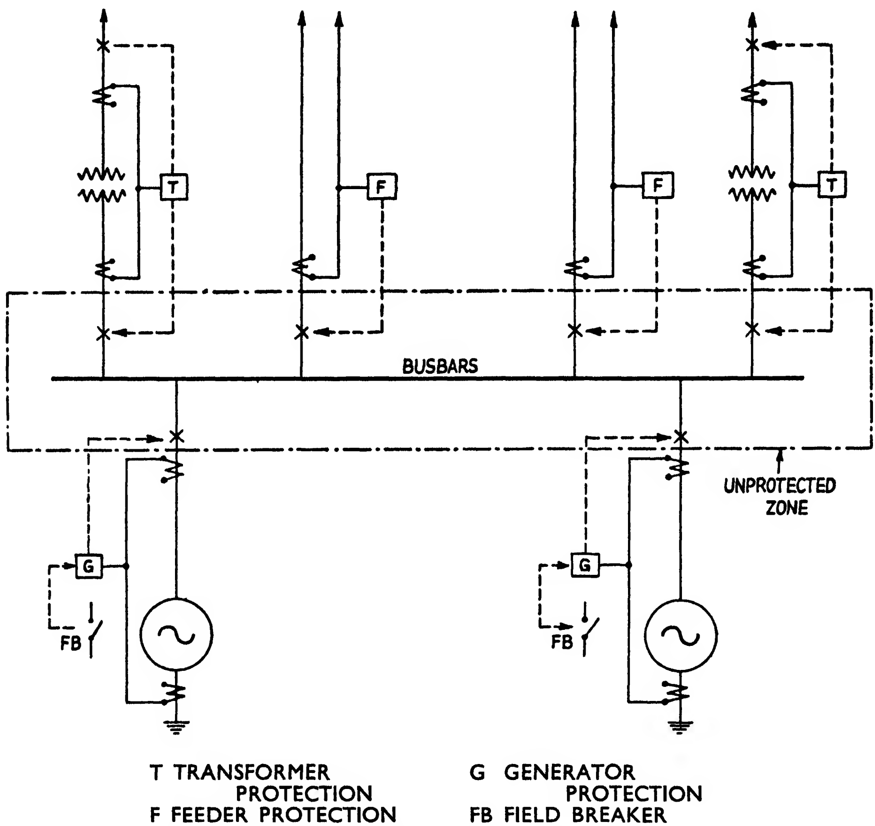


FIG. 15-80.—*Diagram illustrating unprotected zone in power station.*

The ideal system of applying protective gear to a power system is for each component to be protected by a high-speed discriminative scheme which provides for each adjacent protective scheme to overlap (as shown in Fig. 15-81), thus leaving no item unprotected, but isolating only the section which is faulty. Economic considerations, however, often dictate that deviation from the ideal must be accepted.

Space does not permit a detailed description to be given of the many forms of busbar zone protection. For such details the reader should make reference to descriptions which are given in some of the papers and books noted in the bibliography and, also, to special literature issued by the manufacturers, notably A. Reyrolle & Co. Ltd., The General Electric Co.

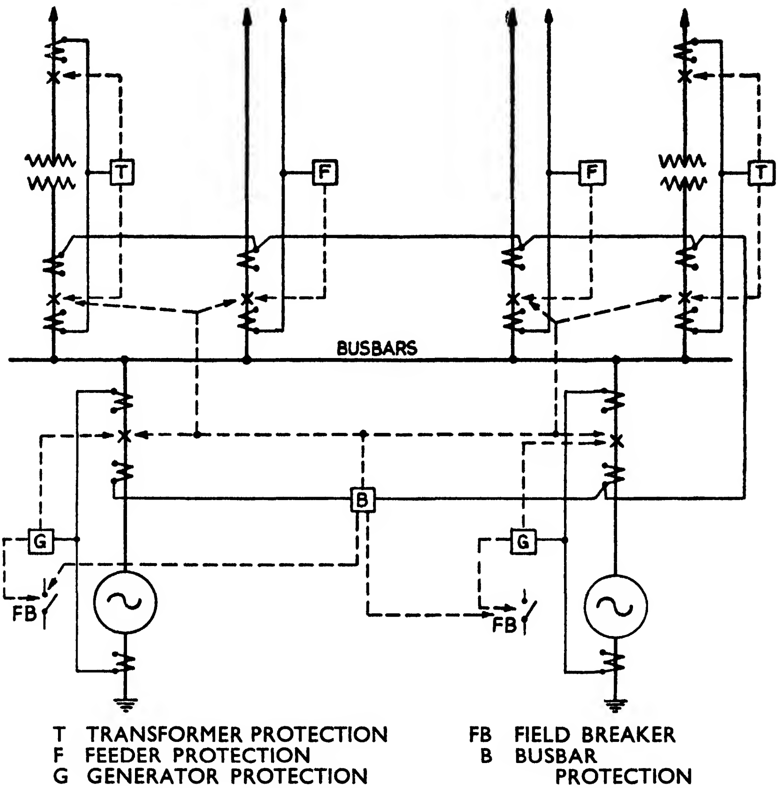


FIG 15-81 --*Diagram illustrating overlap protection to cover busbar zone*

Ltd., Associated Electrical Industries Ltd., and The English Electric Co. Ltd.

It will be convenient, however, to note two schemes: (a) that known as "Leakage to Frame" which is applied to relatively simple layouts of metalclad switchgear, and (b) the "Mono-bias" scheme of A. Reyrolle & Co.

In (a) protection against earth-faults only is given, means being provided to ensure that any current flowing to earth—as a consequence of a switchgear fault—will flow through a fault detecting device. It requires the insulation from earth of the main switchgear framework, the main cable glands, and any auxiliary cable glands, as shown in Fig. 15-82.

The framework is bonded to earth at one point, and a current transformer is mounted on the bonding connections. The fault current due to earth-faults within the busbar zone, i.e. to the switchgear framework, flows from the framework to earth through the current transformer primary and thus energises the simple relay sequence, bringing about the tripping of all circuits connected to the busbars.

The "Leakage-to-Frame" system requires a minimum of equipment and is used extensively with switchgear of the smaller breaking capacities. Special insulation between the framework and earth is not considered necessary, so

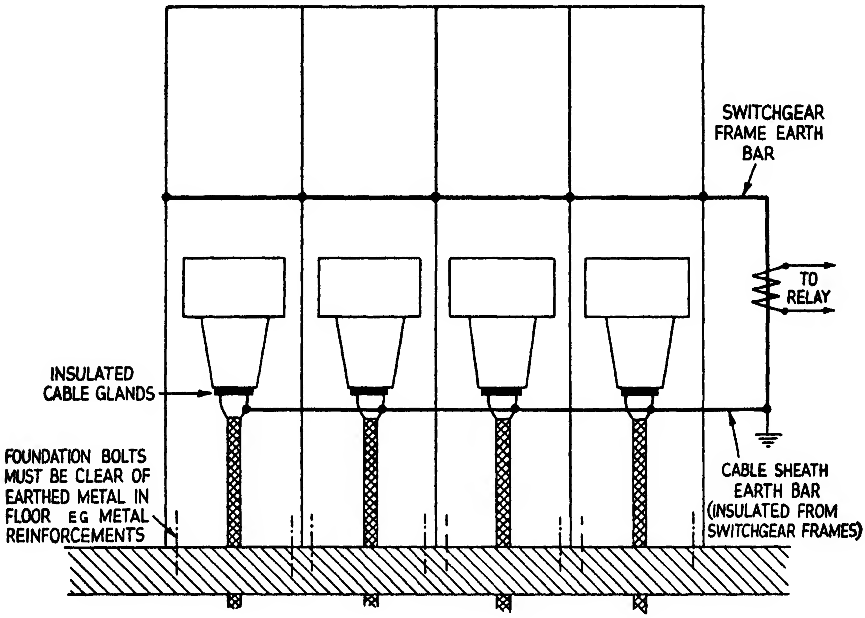


FIG. 15-82.—*"Leakage to Frame" bus-zone protection.*

long as the holding-down bolts are kept reasonably clear of reinforcing and similar metalwork; insulation resistances of 5 to 10 ohms are then obtained. The main cable glands however, must have insulation of a flashover value of 12 to 13 kV in order to prevent flashover from induced voltage in the cable sheaths during faults.

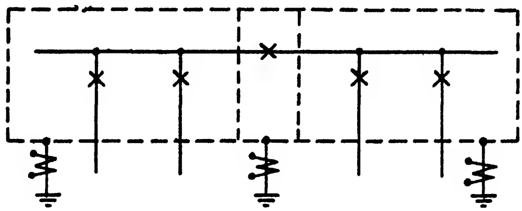
To check the flow of primary earth-fault current before allowing tripping to take place, it is usual to provide an earth-fault relay operated from current transformers at the neutral earthing points or in the incoming circuits, as shown. This gives two simple independent lines of defence, and prevents inadvertent tripping by current flowing in the frame as a result say, of the accidental short-circuiting of an auxiliary supply.

The system can be applied to sectionalised switchboards in two ways, as shown in Fig. 15-83. In (a) the section switch is insulated from both sections of the switchgear, three zones of insulation being formed. A fault in a section of switchgear would result in the tripping of the faulty section only, but a fault in the section switch zone would result in the tripping of all the circuits connected to the switchboard because the fault may be on either side of the section switch.

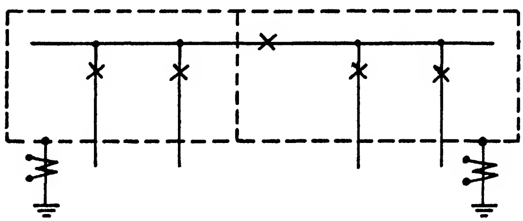
A two-zone system is sometimes used with sectionalised switchboards the section switch being included in one of the zones, as shown in (b) of Fig. 15-83. Provision is made, however, to trip the left-hand zone after a

discriminative time lag, if the fault current persists after the tripping of the right-hand zone. This ensures the complete clearance of a fault between the

(a)



(b)



(c)

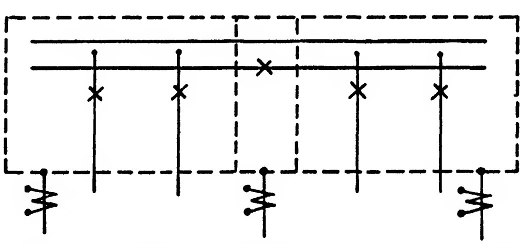


FIG. 15-83.—*"Leakage to Frame" bus-zone protection.*

section switch and the insulating barrier. In such an arrangement, it is desirable to have the earthed source of power connected to the left-hand section or, alternatively, to have a source of earth-fault current connected to each section.

The scheme is applied to duplicate busbar installations as shown in Fig. 15-83 (c). Owing to the practical difficulties of insulation between main and reserve busbars, discrimination between busbars is nor possible. The scheme shown in (c) would operate as shown in (a) with the addition that all circuits connected to the reserve busbar would be tripped, irrespective of the position of the fault.

The "Mono-bias" system was developed to meet increasing demands for higher fault clearance speeds and higher transient stability. It is based on the Merz-Price principle of current balance, but it also has a novel biasing feature, which is effective for external faults of all kinds. Two independent lines of defence for stability with external faults are normally provided, both of the biased Merz-Price balance type.

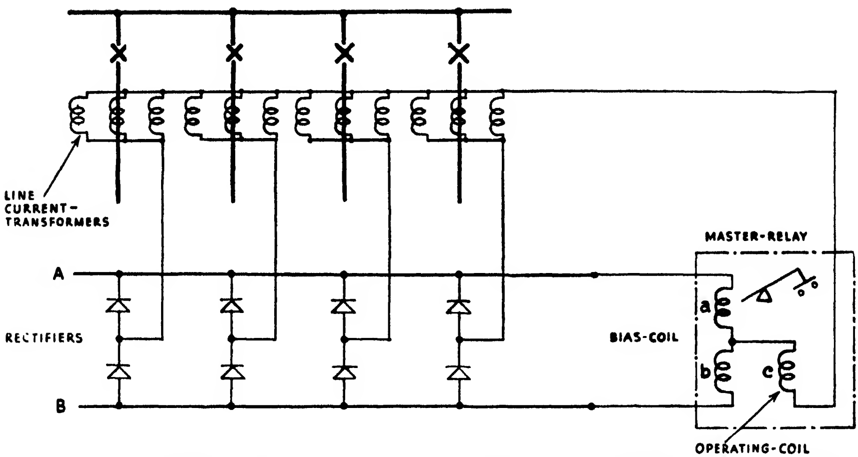


FIG. 15-84.—*"Mono-bias" bus-zone protection (A. Reyrolle & Co. Ltd.).*

The essential connections of the "Mono-bias" system are shown in simplified form in Fig. 15-84, which illustrates its application to a single section of busbar with four circuit-breakers. Each primary circuit has three current transformers with their secondaries in parallel and connected through opposite-polarity rectifiers to two bus-wires A and B. The master relay may be considered as having two equal bias coils connected across the bus-wires, an operating coil connected between the junction of the bias coils, and a common bus-wire joining one side of the current transformers.

At any instant during an external fault, the secondary current in the current transformers carrying fault current towards the busbars is opposite in polarity to that in the current transformers carrying fault current away from the busbars. This means that while current is fed from one current transformer group through a positively-connected rectifier to bus-wire A, an equal current is fed from bus-wire B through a negatively-connected rectifier to the other current transformer group. This happens no matter which half-cycle of fault current is considered. If current flows into bus-wire A and out of bus-wire B for both half-cycles of fault current, the bias coils, "a" and "b" must carry full-wave rectified current. It can also be shown that similar conditions obtain when the external fault is fed into and out of the busbars by any number or combination of circuits and that the value of the full-wave rectified current through the bias circuit is the secondary current equivalent to the arithmetic sum of the outgoing or incoming fault currents. On the other hand, the operating coil "c" carries the difference between the current fed into bus-wire A, and the current fed away from bus-wire B, i.e. the vector sum of the secondary equivalent of the total fault current. Theoretically, this should be zero with an external fault but, in practice, there is a small "spill" current. Under these conditions the control exerted by the bias coil is much greater than that exerted by the operating coil, and the relay restrains. For the purpose of illustrating the principle of the protection, the relay in Fig. 15-84 is shown as a beam-type relay; the actual "Mono-bias" relay is described later.

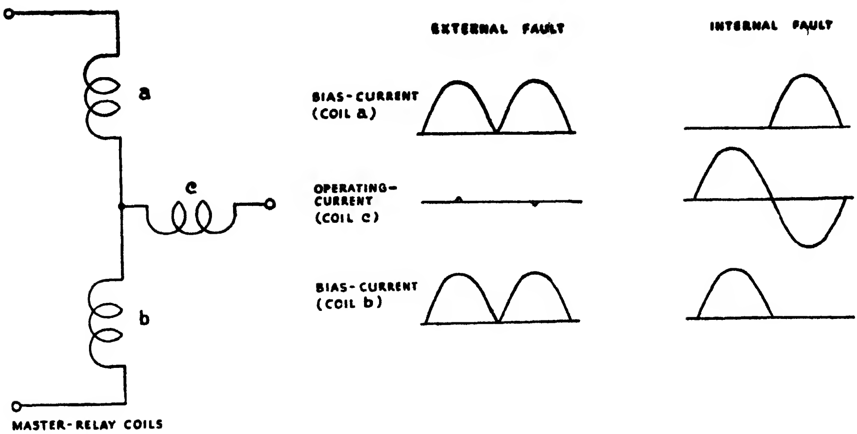


FIG. 15-85.—*Relay characteristics—"Mono-bias" bus-zone Protection (A. Reyrolle & Co., Ltd.).*

With an internal fault, the direction of the fault current at any instant is the same in all circuits in which it flows. Thus, during one half-cycle the secondary current from the current transformer groups carrying fault current, is fed through the positively-connected rectifiers to bus-wire A, through the bias coil "a" and the operating coil "c" and back to the current transformers by the common bus-wire. In the next half-cycle the secondary current from the current transformers is fed from the current transformer common bus-wire, through the operating coil "c", and the bias coil "b" and back through the negatively-connected rectifiers to the appropriate current transformer groups. With internal faults, therefore, the operating coil "c" carries the secondary current equivalent to the total fault current, whereas the bias coils "a" and "b" carry alternate half-cycles of secondary current in the same direction. Under these conditions the operating ampere-turns exceed the bias ampere-turns and the relay operates.

Fig. 15-85 shows the wave-form of the currents carried in the three coils "a", "b" and "c" with external and internal faults.

The actual relay used in this scheme has three components, namely, a relay transformer, a bridge rectifier and a telephone relay, arranged as shown in Fig. 15-86. The bias coils "a" and "b" consist of a centre-tapped winding on the middle limb of a three limbed high-permeability transformer core, and the operating coil "c" consists of two windings, one on each outer limb. The middle limb also has a short-circuited winding, and the outer limbs have output secondary windings which are connected to the d.c. telephone relay through the bridge rectifier.

As has previously been described, the bias coils "a" and "b" can be considered as carrying, during external faults, a full-wave rectified current equivalent to the fault current. This produces a practically constant un-directional flux in the middle and outer limbs because the short-circuited winding operates to prevent flux changes, i.e. so that the flux is smoothed. The core is highly saturated and, hence, even relatively large out-of-balance

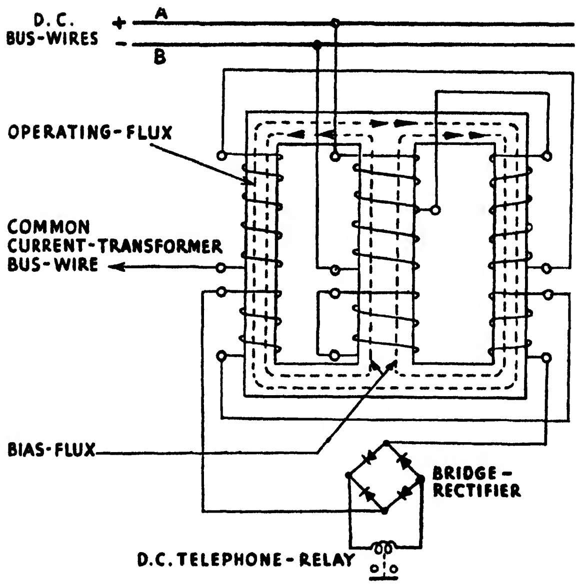


FIG. 15-86.—*Relay as used in "Mono-bias" bus-zone protection (A. Reyrolle & Co. Ltd.).*

currents in the operating coil "c" cause practically no flux-changes and, therefore, no output to the d.c. relay. The protection thus remains stable.

With internal faults, the biasing effect is only half of what it is with an external fault, because the current flows in the bias coils "a" and "b" only in alternate half-cycles. Also, the operating coil "c" carries the secondary equivalent of the total fault current. The a.c. operating ampere-turns are now sufficient to overcome the biasing ampere-turns and to produce flux changes which cause voltages to be induced in the secondary windings and, thus, to operate the d.c. relay.

There have been many recent developments in busbar zone protection such as those in which the moving coil relay with harmonic restraint have been employed (see paper by Ryder, Rushton, and Pearce and article by Rushton and Wellman, both noted in the bibliography) and a high impedance scheme introduced by A. Reyrolle & Co. Ltd., operating on the differential current-balance principle, the high impedance relay circuit being utilised to provide stability as against the bias method employed in "Mono-bias", which is a low-impedance scheme. In this scheme also, phase-fault settings equal to those for earth-faults are obtained whereas in "Mono-bias" the former are higher than for earth-faults.

PROTECTIVE CURRENT AND VOLTAGE TRANSFORMERS*

In Chapter XVI we shall note some of the features of current and voltage

* *During the life of this edition of the J. & P. Switchgear Book, revisions to B.S.81 and B.S. 2046 are anticipated, probably combining current transformers in one new specification and voltage transformers in another. Such new standards, if and when issued, should be regarded as superseding the data herein.*

transformers as used for the operation of instruments and meters, such transformers complying with B.S.81.

The requirements for transformers for these purposes are, however, often such as to be the opposite of those necessary for protective purposes as, for example, in the matter of accuracy. In the case of current transformers, those for metering purposes require to be accurate up to about 20 per cent overload and will not be concerned with the measurement of heavy overcurrents. On the other hand, protective current transformers require to be accurate at currents above the rated current up to a high maximum so that the fault current is accurately reproduced in the secondary circuit for sensing by the protective system. The requirements of current transformer performance for protective purposes will differ as between non-balanced schemes and those in which balance is the criterion.

Voltage transformers differ as between those used for metering purposes and those used for protection in that the latter require to be accurate at voltages below the normal, this being a condition arising when a fault occurs. They must, in certain forms of protection, be such as to provide a secondary residual voltage, as we have noted earlier in our discussion on directional earth-fault protection and the performance characteristics of the winding producing this voltage must be defined.

In 1953, therefore, protective current and voltage transformers were removed from the sphere of B.S.81 * "Instrument Transformers" and a new specification was issued, B.S.2046*, to cover the performance requirements of and the special characteristics applicable to current and voltage transformers for protective purposes. At the moment, this specification applies to transformers intended for use in non-balanced schemes such as overcurrent devices, both of the non-directional and directional types and for earth-fault relays with inverse definite minimum time-lag characteristics.

The characteristics of protective transformers for other forms of protective gear where it is more precisely dependent on the magnitude and phase relationship of current and voltage (residual current detection on a system earthed through an arc-suppression coil is one example) or where the protective system is dependent on balance as in the differential schemes described earlier, may require characteristics not covered by B.S.2046 and the advice of the designers of the particular protective system must be sought.

The introduction of B.S.2046 shows two new terms in relation to protective current transformers namely "rated primary saturation current" and "rated saturation factor". The former is the maximum primary current at which the transformer will retain its prescribed accuracy while the latter is the ratio of the rated primary saturation current to the rated primary current. Four standard factors are specified, 5, 10, 15, and 20, with a recommendation that a saturation factor of 10 be used for general purposes. Thus, if this factor is acceptable a given current transformer would maintain its ratio within prescribed limits for primary currents up to 10 times the rated primary current. One of the reasonings behind the recommended saturation factor of 10 is that many relays are not appreciably affected by further increase in operating current once they have reached the limiting time-characteristic and it is thus possible for the associated current transformer to be designed to saturate at or just above this point, and the choice of 10 as a general purpose saturation factor is based on satisfactory experience in service in relation to relay performance as noted plus a study of the effects

of saturation in the magnetic circuit of current-operated relays on over-currents.

In Chapter XVI, we shall consider the need to design current transformers to withstand the electromagnetic and thermal effects due to the passage of fault current in the primary for short time intervals. These considerations will apply equally to protective current transformers.

Three classes of accuracy, designated by the letters S, T and U are recognised in B.S.2046, and the limits of ratio error at (a) rated primary current and (b) at any current above (a) up to rated primary saturation current, are given in Table 15:1.

TABLE 15:1

Class	Ratio error at rated primary current (a)	Ratio error above rated primary current up to rated primary saturation current (b)
	per cent	per cent
S	±3	±3
T	±5	±10
U	±7·5	±15

The maximum values of phase error for these classes are respectively 2°, 6° and 9°.

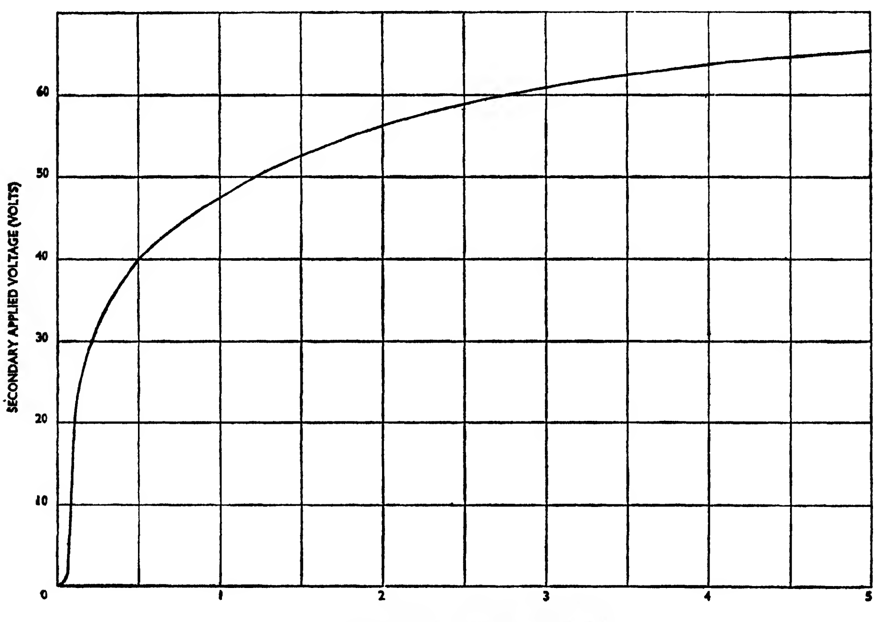


FIG. 15-87.—*Typical magnetisation curve for a 50/5 ampere wound primary protective current transformer.*

Fig. 15-87 shows a typical magnetisation curve for a 50/5 ampere wound primary current transformer designed for a protective Class S, with a burden of 15VA and having a saturation factor of 10.

The limits of ratio error and phase difference for voltage transformers are given in Table 15:2.

TABLE 15:2

Applied primary voltage	Burden at unity p.f.	Ratio error	Phase difference
Per cent of rated voltage	Per cent of rated burden	Per cent	Degrees
50 and 110	100 to 25	±2·5	±2·5
5 and 10	100 to 25	±5	±5

Appendix B in B.S. 2046 is an excellent general guide to the determination of the appropriate ratings of a protective current transformer for a number of specific purposes and this and a study of the papers noted in the bibliography will repay the student or user interested in this now specialised section of the protective gear art.

BIBLIOGRAPHY

B.S. 142. Protective Relays.

B.S. 2046. Protective Transformers.

Automatic Protection of A.C. Circuits. G.W. Stubbings (Chapman & Hall, Ltd.)

Electrical Engineers' Reference Book (George Newnes, Ltd.).

Electric Power System Control (3rd Ed.), H.P. Young (Chapman & Hall, Ltd.)

Protective Gear Handbook. M. Kaufman (Pitman & Sons).

Protective Relays. A. R. Van C. Warrington (Chapman & Hall, Ltd.).

Switchgear Principles. P. H. G. Crane (Cleaver-Hume Press Ltd.).

"PROTECTION OF DISTRIBUTION NETWORKS." J. W. Richardson. "The Mining Electrical and Mechanical Engineer." February, 1959.

"EARTH-FAULT PROTECTION ON MEDIUM-VOLTAGE SYSTEMS." P. T. Thornhill. "The Metropolitan-Vickers Gazette," March, 1951.

"A METHOD OF EARTH-FAULT PROTECTION WITH CURRENT LIMITATION." E. Loynes and F. Crowther. "The Mining Electrical and Mechanical Engineer," February, 1961.

"APPLICATIONS AND LIMITATIONS OF INVERSE-TIME OVERLOAD RELAYS TO THE PROTECTION OF AN 11kV NETWORK." J. W. Gallop and R. H. Bousfield. Journal I.E.E., 1940, Vol 87, p. 113.

(1) "APPLICATION OF INVERSE-TIME OVERCURRENT RELAYS." R. W. Newcombe. "English Electric Journal," Vol. XIV, No. 5, March, 1956.

(2) "INSTANTANEOUS BALANCED CURRENT PROTECTION." J. Rushton and F. E. Wellman. "The Metropolitan-Vickers Gazette," May-June, 1951.

"THE PROTECTION OF ELECTRICAL POWER SYSTEMS: A CRITICAL REVIEW OF PRESENT-DAY PRACTICE AND RECENT PROGRESS." H. Leyburn and C. W. Lackey. Proceedings I.E.E. Paper No. 1135S, February, 1952, Vol. 99, Part II, p.47.

"A MOVING-COIL RELAY APPLIED TO MODERN HIGH-SPEED PROTECTIVE SYSTEMS." C. Ryder, J. Rushton and F. M. Pearce. Proceedings I.E.E., Paper No. 1450M, June, 1953. Vol. 100, Part II, pp.261-273 (reprinted without appendices in the "Metropolitan-Vickers Gazette," November, 1953).

"ELECTRICAL PROTECTION OF TURBINE-GENERATORS." C. Ryder "Electrical Review," 28th August, 1959 (reprinted in the "Metropolitan-Vickers Gazette," November, 1959).

(3) "ELECTRICAL PROTECTION OF LARGE GENERATOR UNITS," R. W. Newcombe. "The English Electric Journal," May, 1959.

"INSTANTANEOUS BALANCED CURRENT PROTECTION," J. Rushton and F. E. Wellman. "The Metropolitan-Vickers Gazette," May/June, 1951.

"THE APPLICATION OF TRANSDUCTOR RELAYS TO PROTECTIVE GEAR," R. K. Edgley and F. L. Hamilton. "Proceedings I.E.E.", August, 1952, Vol. 79, Part II.

"TRANSFORMER AND PROTECTIVE GEAR CIRCUIT ANALYSIS," A. Salzmann. "Electrical Review," 4th November, 1955.

(4) "INTERTRIPPING REMOTE CIRCUIT-BREAKERS," A. P. Gordon and J. Rushton. "The Metropolitan-Vickers Gazette," July/August, 1950

(5) "The Protection of Tee'd Feeders," J. Rushton and F. A. Stacy. "The Metropolitan-Vickers Gazette," October, 1952.
(6) "HIGH-SPEED CARRIER CURRENT PROTECTION," M. Kaufmann and J. W. Hodgkiss "Electrical Times," 5th August, 1945.
"THE PROTECTION OF BUSBARS AND SWITCHGEAR," A. Fitzpatrick, "G.E.C. Journal," July, 1950.
"BUSBAR PROTECTION—THE THEORY AND APPLICATION OF MODERN SYSTEMS," I. A. Reid, "Electrical Review," 7th June, 1957 (reprinted in "The Metropolitan-Vickers Gazette," June, 1957).
(7) "THE DEVELOPMENT OF BUSBAR PROTECTION," R. W. Newcombe, "The English Electric Journal," June, 1956.
"VOLTAGE TRANSFORMERS AND CURRENT TRANSFORMERS ASSOCIATED WITH SWITCHGEAR," W. Gray and A. Wright. "Proceedings I.E.E." Paper No. 1398M, June, 1953, Vol. 100. Part II, p.223.
"PROTECTIVE CURRENT TRANSFORMERS," A. A. Halacsy, "Electrical Times," 8th July, 1954.
"CURRENT TRANSFORMERS—THEIR BEHAVIOUR ON BALANCED CIRCUITS," J. H. Toule, "Electrical Review," 15th July, 1955.
"THE FUNDAMENTAL CHARACTERISTICS OF PILOT-WIRE DIFFERENTIAL PROTECTION SYSTEMS," J. Rushton "Proceedings I.E.E.", Paper No. 3645S, October, 1961.
"INTRODUCTION TO DISTANCE RELAYING," R. W. Newcombe, "Electrical Review," 13th April, 1962.

Note: Articles numbered thus, (1), (2), etc., are available as reprints from various manufacturers as follows:—
(1) English Electric Co. Ltd.—reprinted as a publication No. M.S./3813.
(2) Associated Electrical Industries Ltd.—reprinted as a descriptive leaflet No. 2207-1.
(3) English Electric Co. Ltd.—reprinted but unnumbered.
(4) Associated Electrical Industries Ltd.—reprinted as a descriptive leaflet No. 2215-1.
(5) Associated Electrical Industries Ltd.—reprinted as a descriptive leaflet No. 343/21-1.
(6) Associated Electrical Industries Ltd.—reprinted as a descriptive leaflet No. 343/15-1.
(7) English Electric Co. Ltd.—reprinted as a publication No. M.S./3816.

In the books by Kaufmann and Stubbings, chapters dealing with the maintenance and testing of protective gear are valuable for study.

In the "J. and P. Transformer Book," 9th edition, further data on transformer protection against surges and faults is given, coupled with information on transformer failures and their causes.

CHAPTER XVI

INSTRUMENTS AND INSTRUMENT TRANSFORMERS

CHAPTER XVI

INSTRUMENTS AND INSTRUMENT TRANSFORMERS

In this chapter it will be our purpose to discuss (a) those indicating instruments most regularly used on switch and control boards and (b) the instrument transformers (current and voltage) which, in the majority of cases, are necessary for the operation of such instruments.

In considering the instruments themselves, no attempt will be made to go into design details, these being more appropriately dealt with in specialist books on the subject and here discussion will be confined mainly to application. When dealing with instrument transformers however, some details of design will be studied because they form a significant part of a switchgear unit, current transformers in particular being subject to the effects of short-circuit as discussed in other chapters.

INDICATING INSTRUMENTS

The instruments normally required on any switchgear installation are those which give an indication of current, voltage, power (watts or kilowatts), frequency and power factor.

Modern instruments for these purposes can be supplied in a variety of types and sizes, e.g. round or square cases, projecting or flush mounting, open or protected dials and with scales of varying length. Cast-iron as a material for the case is still used in some instances as for example sector and controller types of instrument but for switchgear or control board use, the pressed steel case is almost universal giving a neater appearance and being much lighter in weight.

Considerable attention has been given in recent years to "appearance design" of both switchboards and control boards, one feature of which has been to reduce to a minimum the number and magnitude of projecting parts and a natural consequence has been the greater use of flush mounting instruments instead of the projecting type which at one time was standard practice.

Switchgear has, at the same time, been reduced in dimensions and this has led to a more general acceptance of the 4 inch instrument or at the most, 6 inch, instead of the space consuming 8 inch type. The miniaturisation of remote control has depended largely on the use of smaller instruments and with the modern open scale, often extending to 240° or more, nothing has been lost in clarity or ease of reading.

Whether the instruments chosen are round or square is a matter of individual preference but as the panels on which they are usually mounted are rectangular in shape, the square instrument tends to maintain the overall pattern.

Whatever the type, an indicating instrument should have a clear, openly divided scale and not be crowded with division marks. The scale markings chosen should be such that the normal reading will be at a point beyond the middle and up to about three-quarters of the scale length. In

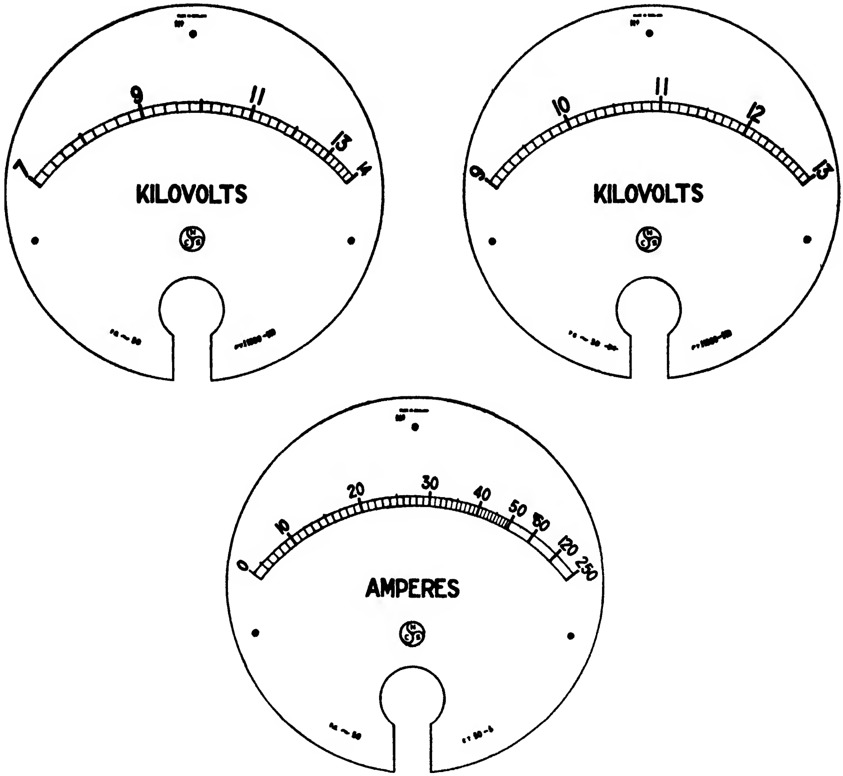


FIG. 16-1.—*Examples of suppressed scale markings.*

some applications, scale suppression may be useful, one example being scales used for voltmeters where the only part of the scale of value is that near the system voltage to be indicated, and here the scales may be in the form shown in the two upper sketches in Fig. 16-1. Another example is that of an ammeter used on a motor circuit and here a suppressed overload scaling as shown in the lower sketch Fig. 16-1 is useful, not only to indicate the starting current which, in an induction motor, may be about six or eight times the normal full-load current, but also to buffer the movement and pointer at the upper end of the scale.

This book is, almost wholly, concerned with switchgear for use on a.c. systems but it will not be out of place to refer first to the moving-coil type of indicating instrument which is essentially d.c. There are a number of applications for this type on a.c. systems as for example in the d.c. exciter circuit of an a.c. generator. Some users prefer a moving-coil instrument on a.c. circuits because of its evenly divided scale over the full deflection and this is readily achieved by the inclusion (often within the instrument case) of a small rectifier. Typical examples of the moving-coil instrument are shown in Fig. 16-2, the normal use being for ammeters and voltmeters.

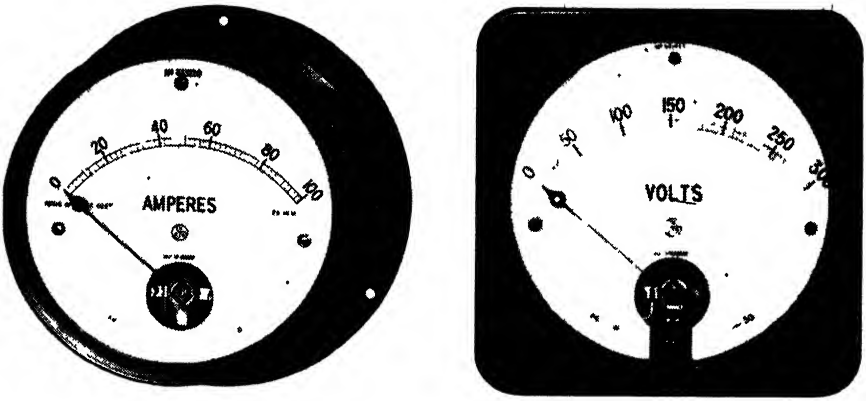


FIG. 16-2.—*Typical-moving coil (left) and moving-coil rectifier (right) instruments (Nalder Bros. & Thompson Ltd.).*

The movement comprises a pivoted moving-coil working in the airgap of a uniform field produced by an internal cylindrical magnet. On d.c. circuits, ammeters are operated from shunts mounted in the primary circuit, the shunts having a 75 millivolt drop for full scale deflection, the instrument being calibrated with shunt leads having a resistance of 0·025 ohms. Voltmeters can normally be direct-connected on systems up to 500/650 volts depending on size of instrument but for higher voltages, externally mounted resistance boxes are employed.

The instrument which is most regularly used on a.c. circuits is the moving-iron type for current or voltage indication. In this type the scale is not evenly divided, being slightly contracted at the lower and upper ends

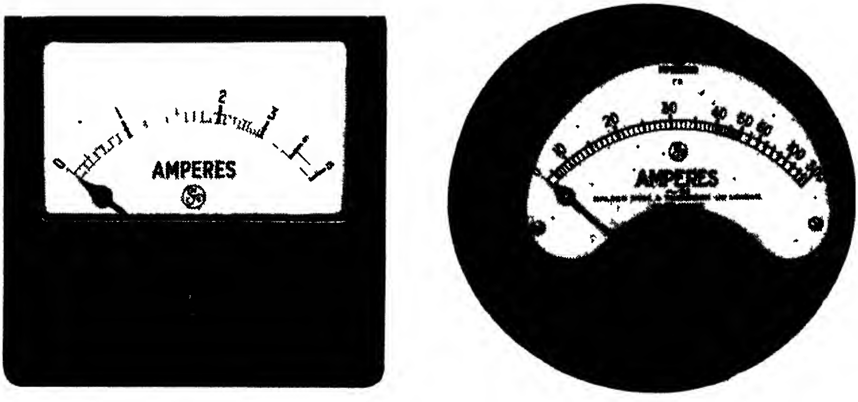
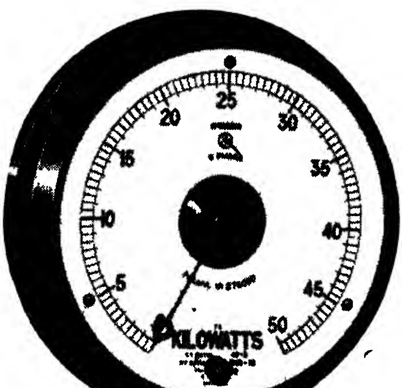
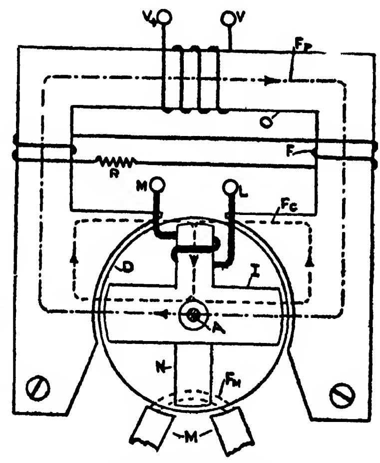


FIG. 16-3.—*Typical moving-iron instruments showing ammeter overload scales (Nalder Bros. & Thompson Ltd.).*

as seen in Fig. 16-3, the instrument operating on the well-known principle of repulsion between fixed and movable irons located in a magnetic field at the centre of a coil. Ammeters of this type can, within certain limits and up to 600 volts, be of the whole current (series connected) type but in some circumstances this has disadvantages (a) because heavy current primary conductors must be taken to the instrument and (b) because the fault current on a short-circuit occurring in the circuit containing the instrument must be carried by the coil, with great risk of damage or even destruction. The use of whole current ammeters therefore should be restricted to circuits where the possible fault current is not high. For these reasons, operation from the secondary of a current transformer is much preferred. Voltmeters may be direct-connected up to 300/650 volts depending on the size of the instrument or may be operated from the secondary of a voltage transformer, usually at 110 volts. It may be noted, in passing, that the moving-iron instrument can be used on d.c. but this is not common practice.

For the indication of power in a circuit, the induction type instrument shown in Fig. 16-4 is generally chosen, the scale being marked in watts,





INDUCTION WATTMETER
LIPMAN TYPE

FIG. 16-4.—*Typical induction wattmeter and schematic diagram of the fixed and moving systems of a single phase single-element instrument (Nalder Bros. & Thompson Ltd.).*

kilowatts or megawatts according to requirements. As the illustration shows, the scale markings are evenly divided over the whole scale and the latter extends over approximately a 300° angle. The movement consists of two parts—a fixed system embodying an external U-shaped electromagnet carrying a shunt (voltage) winding and an internal core of cruciform shape, on one of the polar projections of which is mounted the series (current) coil, and a moving system consisting of a thin aluminium cylinder which is free

to rotate in the airgap between the poles of the external and internal electromagnets. This cylinder is attached to a spindle supported in jewelled centres and carries the indicating pointer.

To measure power, both current and voltage elements are essential, the appropriate coils being either direct connected up to about 25 amperes and 650 volts or operated from the secondaries of current and voltage transformers. The number of current and voltage elements employed in a particular instrument will depend on the nature of the system e.g. whether single phase, two phase, 3-phase 3 wire, or 3-phase 4 wire and whether for balanced or unbalanced load circuits. A series of connection diagrams given in Appendix C, will indicate these various applications.

It is of interest to note that the induction wattmeter movement suitably modified can be employed in an instrument to measure the wattless or idle component of the current and this instrument is then described as a "reactive volt-ampere meter". If the voltage of a system is maintained constant, the instrument can be calibrated to read the idle component of the current in amperes and is then described as an "idle current ammeter".

The once popular "vibrating reed" or resonance type of frequency meter has now been completely superseded by the deflectional type shown in Fig. 16-5, in which the pointer moves over a very open scale to indicate

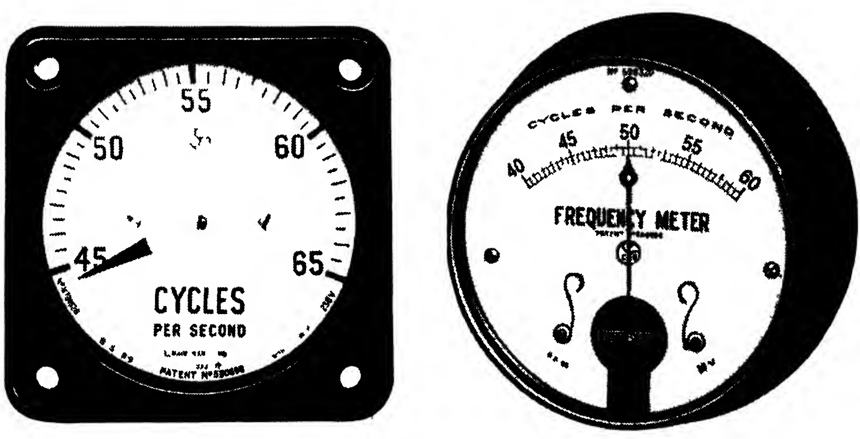


FIG. 16-5.—*Typical deflectional type frequency meters (Nalder Bros. & Thompson Ltd.).*

the instantaneous value of frequency of an a.c. system. This meter operates on the basis of a ratio meter in which the moving system comprises two coils connected respectively in two parallel circuits, one comprising a non-inductive resistance and the other circuit tuned to resonance at the higher value of the required frequency range.

Power factor meters, as implied by the name, are designed to show the power factor or angle of lag or lead between current and voltage. A knowledge of the system power factor is of importance both to power station engineers and to commercial and industrial users, the latter being particularly

interested in the light of power factor clauses which appear in tariff agreements, and to the now considerable application of power factor correction capacitors to achieve a power factor which avoids any penalising charge.

The instruments shown in Fig. 16-6 are of the Lipman moving-iron type operating on what is described as the "component field" theory.

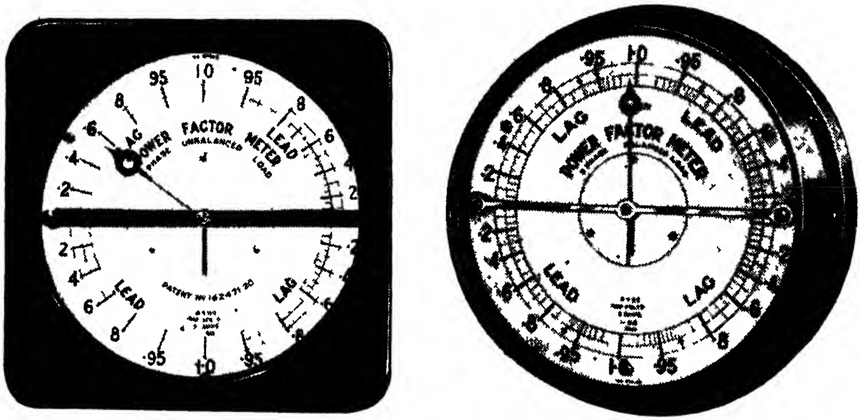


FIG. 16-6.—*Typical power factor meters (Nalder Bros. & Thompson Ltd.).*

In this there is a fixed system comprising a set of field coils and a set of magnetising coils, the former energised by the current from the line, either directly or from current transformer secondaries and the magnetising coils energised from the pressure (voltage) circuit either directly or from the secondary of a voltage transformer. The moving system consists of a number of thin iron plates of special shape attached to a spindle which carries the pointer. This rotor system when magnetised, rotates to take up a position related to the power factor of the system to which it is connected, the pointer showing whether the current is leading or lagging relative to the voltage. If the pointer takes up a position in the upper half of the scale it indicates forward power, e.g. generators to line, and if in the lower half, reverse power, i.e. lines to load.

As in the case of wattmeters, the number of current and voltage elements will depend on the nature of the system to which an instrument is to be connected, i.e. single, two or three phase, three or four wire, balanced or unbalanced loading and here again a series of diagrams are given in Appendix C to cover the various conditions.

INSTRUMENT TRANSFORMERS*

In order to distinguish a difference, current and voltage transformers as used for the operation of any of the indicating instruments noted earlier or for integrating meters of any kind, will be called "instrument transformers" to avoid confusion with such transformers used for protective systems for

**During the life of this edition of the J. & P. Switchgear Book, revisions to B.S. 81 and B.S. 2046 are anticipated, probably combining current transformers in one new specification and voltage transformers in another. Such new standards, if and when issued, should be regarded as superseding the data herein.*

which very different requirements are necessary. In an instrument current transformer we are concerned mainly with its accuracy (ratio and phase angle errors) between the limits of 10 per cent and 120 per cent of rated current, whereas in protective current transformers we are much more concerned as to their behaviour when carrying fault currents often in the tens of thousands of amperes. This latter consideration and some of the special requirements of voltage transformers associated with protective gear have been dealt with in Chapter XV.

It has been noted earlier that when the current and/or voltage is low, instruments may be direct-connected without the intervention of current or voltage transformers. On the other hand circumstances may require these to be used regardless of the system voltage or the low current rating. On high-voltage switchgear transformers will always be employed, those for current having secondaries giving 5 or 1 amperes (in some exceptional cases 0·5 amperes) and those for voltage giving 110 volts at the secondary terminals.

CURRENT TRANSFORMERS

It has been noted that a design consideration is that ratio and phase angle errors must be within certain limits from 10 per cent to 120 per cent of rated current and these limits are given in Table 16 : 1.

TABLE 16 : 1

LIMITS OF ERROR AT RATED BURDEN AND FREQUENCY AT UNITY P.F. (SEE CLAUSE 17–B.S. 81 : 1936)

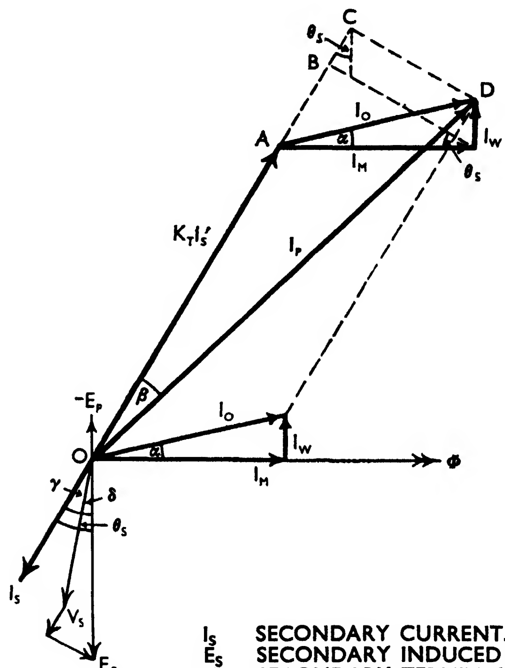
Class	AM	BM	CM	A	B	C	D
From 120% to 20% of rated current							
Ratio error, % (+ or −) ..	1	1	1	0·5	1	1	5
Phase error, mins (+ or −) ..	30	35	90	35	60	120	—
From 20% to 10% of rated current							
Ratio error, % (+ or −) ..	1	1·5	2	1	1·5	2	—
Phase error, mins (+ or −) ..	30	50	120	50	90	180	—
Variations in error—							
From 120% to 10% of rated current							
Ratio error, %	0·5	1	1·5	—	—	—	—
Phase error, mins	15	25	60	—	—	—	—

The classes of current transformer in Table 16 : 1 are those noted in more detail in Table 16 : 2.

TABLE 16 : 2

Application	Class
Precision industrial metering	AM
Industrial metering, sub-standard grade to B.S. 37	BM
Industrial metering, commercial grade to B.S. 37	CM
Sub-standard indicating wattmeters	A
First grade indicating and graphic wattmeters	B
First grade indicating and graphic ammeters	C
For purposes where ratio is less important than in the above, i.e. ammeters where approx. values only are required.	D

How the errors with which we are concerned arise can best be considered by a study of the vector diagram for a current transformer, as shown in Fig. 16-7.



I_S SECONDARY CURRENT.
E_S SECONDARY INDUCED EMF.
V_S SECONDARY TERMINAL VOLTAGE.
E_P PRIMARY INDUCED EMF.
I_P. PRIMARY CURRENT.
$K_T\ I_S'$ REVERSED SECONDARY CURRENT TIMES TURNS RATIO.
I_O EXCITATION CURRENT.
I_M. MAGNETISING COMPONENT OF I_O REQUIRED TO PRODUCE FLUX.
I_W. IN PHASE COMPONENT OF I_O SUPPLYING CORE LOSSES (EDDY CURRENT AND HYSTERESIS).
Φ MAIN CORE FLUX.
δ PHASE ANGLE DUE TO SECONDARY WINDING.
γ PHASE ANGLE DUE TO BURDEN.
$\theta_S=\delta+\gamma$ TOTAL SECONDARY PHASE ANGLE.
α LOSS ANGLE DUE TO CORE EXCITATION.
β PHASE ANGLE BETWEEN PRIMARY AND REVERSED SECONDARY CURRENT.

FIG. 16-7.—*Vector diagram for a current transformer* (*Not to scale*).

When drawing the vector diagram for a current transformer it is usual to commence with the flux as reference vector since this is common to both primary and secondary windings. The induced e.m.f's E_S and E_P lag behind the flux by 90° and can be drawn in, the magnitude of the vectors E_S and E_P being proportional to the secondary and primary turns.

The excitation current I_O taken by the primary, is made up of two components I_M and I_W. I_M is the reactive magnetising component which produces the flux and I_W is the active component supplying the hysteresis and eddy current losses in the core; this is in phase with the primary induced e.m.f. $-E_P$.

The secondary current I_S lags behind the secondary induced e.m,f. by an angle θ_S. θ_S is made up of δ the angle produced by the secondary winding resistance and reactance, and γ the angle produced by the burden connected to the secondary winding. In practice for a bar primary current transformer the secondary winding reactance is usually negligible and δ is zero. The secondary current is now transferred to the primary side by reversing I_S' and multiplying by the turns ratio K_T. The resultant current flowing in the primary winding I_P is then the vector sum of K_T I_S and I_O.

It should be noted that the flux Φ and exciting current I_O are determined by the secondary voltage required which is in turn determined by the burden connected to the secondary winding, or for a given burden by the current flowing in the secondary and primary windings. Hence with a current transformer the flux density in the core is not constant but varies with the primary current, this being the basic difference between a current and voltage (or power) transformer where the voltage and flux density remains constant and the current varies with the load.

There are two main errors introduced into a circuit by a current transformer. These are (a) the ratio error and (b) phase angle error.

(a) *The ratio error*

Since the primary current has to contribute to the magnetising and iron loss components, the ratio of primary to secondary current is not exactly equal to the turns ratio. The error introduced is known as the "ratio error" and is defined in B.S.81 : 1936 as:—

$$\text{Percentage ratio error} = \frac{K_n I_S - I_P}{I_P} \cdot 100$$

$$\text{Where } K_n = \text{Nominal ratio i.e. } \frac{\text{Rated primary current}}{\text{Rated secondary current}}$$

There are two other ratios which are of importance in a current transformer, these are:—

$$K_T = \text{Turns ratio} = \frac{\text{Secondary turns}}{\text{Primary turns}}$$

$$K_C = \text{Actual current ratio} = \frac{\text{Actual primary current}}{\text{Actual secondary current}}$$

By studying the vector diagram it is possible to derive an expression for the ratio error in terms of other known components.

If the reversed secondary current vector OA is produced to a point OC where CD is a perpendicular dropped from the primary current vector OD, then since in practice the angle β is small the length OC is very nearly equal to the length of OD, and all components can be resolved along the OC axis.

$$\text{Now actual ratio } K_C = \frac{I_P}{I_S}$$

$$\simeq \frac{\text{length OC}}{I_S}$$

$$= \frac{OA+AB+BC}{I_S}$$

$$= \frac{K_T I_S' + I_M \sin\theta_S + I_W \cos\theta_S}{I_S}$$

$$= K_T + \frac{I_M \sin\theta_S + I_W \cos\theta_S}{I_S}$$

but $I_M = I_O \cos\alpha$ and $I_W = I_O \sin\alpha$ and if θ_S is very small then the expression can be reduced further:—

$$K_C = K_T + \frac{I_O \cos\alpha \sin\theta_S + I_O \sin\alpha \cos\theta_S}{I_S}$$

$$= K_T + \frac{I_O}{I_S} \sin(\theta_S + \alpha)$$

If now θ_S is very small then:—

$$K_C = K_T + \frac{I_O \sin\alpha}{I_S}$$

but $I_O \sin\alpha = I_W$

$$K_C = K_T + \frac{I_W}{I_S}$$

From this expression it can be seen that for a small secondary phase angle the ratio error is mainly due to the iron loss component of the excitation current.

Another point that emerges from the above expression is that since the actual current ratio is equal to the turns ratio plus I_W/I_S then the magnitude of I_W/I_S determines the amount of turns compensation necessary to reduce the errors to a minimum.

(b) *Phase angle*

The phase angle is also introduced by the fact that the primary current has to supply the components of the exciting current, and the reversed secondary current is not exactly in phase with the primary current. The angle between the two vectors is known as the phase difference of the C.T.

This angle can easily be derived from again studying the vector diagram.

Now since β is very small in practice $\tan\beta \simeq \beta$

$$\therefore \beta = \frac{I_M \cos\theta_S - I_W \sin\theta_S}{K_T I_S + I_M \sin\theta_S + I_W \cos\theta_S}$$

$$= \frac{I_M \cos\theta_S - I_W \sin\theta_S}{K_T I_S + I_O \cos\alpha \sin\theta_S + I_O \sin\alpha \cos\theta_S}$$

$$= \frac{I_M \cos\theta_S - I_W \sin\theta_S}{K_T I_S + I_O \sin(\theta_S + \alpha)}$$

In practice $I_O \sin(\theta_S + \alpha)$ is very small compared with $K_T I_S$ and can be neglected.

$$\therefore \beta = \frac{I_M \cos\theta_S - I_W \sin\theta_S}{K_T I_S}$$

$$= \frac{I_O \cos\theta_S \cos\alpha - I_O \sin\theta_S \sin\alpha}{K_T I_S}$$

$$= \frac{I_O \cos(\theta_S + \alpha)}{K_T I_S}$$

If the secondary phase angle is very small

$$\beta = \frac{I_O \cos\alpha}{K_T I_S}$$

$$\therefore \beta = \frac{I_M}{K_T I_S}$$

From this expression it can be seen that if θ_S is small the phase angle is mainly due to the magnetising component of the exciting current.

The phase angle is usually expressed in minutes.

An improvement in the ratio and phase angle errors can be obtained by a combination of methods:—

(*a*) By the use of high permeability and low loss magnetic material for the core, such as good grade silicon steel (e.g. Special Stalloy), or even nickel steel (e.g. Mumetal) where the increased cost of the latter is justified and provided the limitations of this material are borne in mind.

(*b*) By reducing the length of the flux path in the core and increasing the area of the path, with all joints reduced to a minimum or avoided altogether.

(*c*) By increasing the primary ampere turns, using a "wound type" coil where the short-circuit current permits such a coil structure.

(*d*) By reducing the internal secondary burden as far as possible, which includes its reactance as well as its resistance. Sometimes it may be necessary to use two secondary windings connected in parallel with each other.

(*e*) By keeping the connected burden on the secondary as small as is possible. This may entail the reduction of the secondary current from

5 amperes to 1 ampere in cases where the connected burden is remote from the transformer. The use of one ampere secondaries is not, however, recommended in high ratios, because of the increased induced voltage upon open-circuit under load, which may destroy the interturn and interlayer insulation and may also prove dangerous to life.

(*f*) By specifying the rated burden as near to the actual burden as is possible, because the correction of ratio error by turns compensation will be made for the rated burden and may not necessarily be so close for a lower burden.

With regard to core material, it is often possible to supply a core composed partly of Stalloy and partly of Mumetal in order to give the required accuracy with an economical use of material. The Stalloy content will prevent excessive phase angle error at, say, 60-120 per cent of rated current, whilst the Mumetal content will ensure a reasonable phase angle error at 20 per cent of rated current. Consequently, the desired accuracy will also be secured as cheaply and efficiently as possible and, also, the variation of error over the range will be under control.

Table 16 : 3 gives some indication of what is possible when using composite circular cores of Stalloy and Mumetal with primaries of the bar type. The Stalloy would be in the form of ring stampings, insulated on one

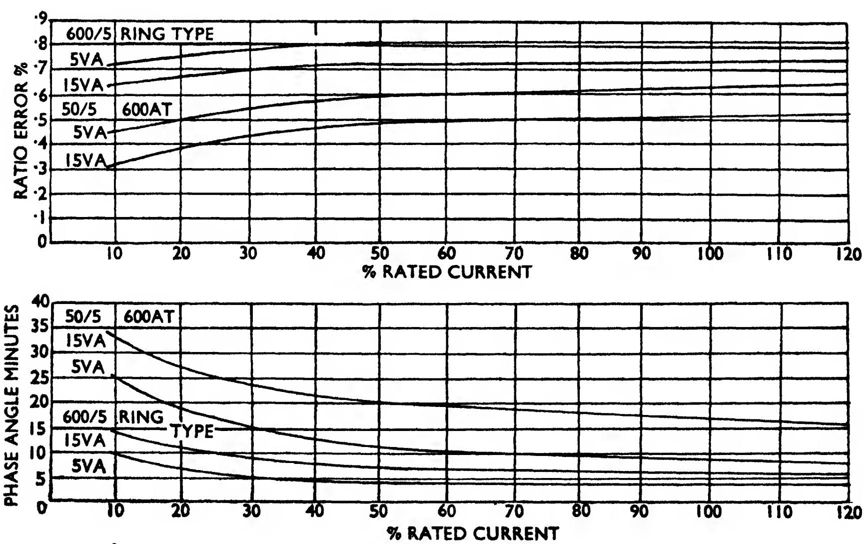


Fig. 16-8.—*Ratio error and phase angle curves for bar primary current transformer* (600/5) *compared with those for a transformer having a wound primary* (50/5) *both working at* 600 *ampere turns.*

side; and the Mumetal in spirally wound rings of 0·5 inch.0·015 inch strip, varnished and taped. The following table gives an indication of the performance of current transformers having different core materials.

TABLE 16 : 3

THE FOLLOWING TABLE GIVES AN INDICATION OF THE PERFORMANCE OF CURRENT TRANSFORMERS HAVING DIFFERENT CORE MATERIALS

Bar primary amps	Silicon iron core (100% Si Fe)		Composite core of Si Fe +Ni Fe (up to 50% Ni Fe)		Composite core of Si Fe +Ni Fe (up to 75% Ni Fe)		Nickel iron core (100% Ni Fe)	
	VA	Class	VA	Class	VA	Class	VA	Class
50	—	—	4 2	D C	2	CM	5	CM
100	15	D	5	C	5	CM or B	3	BM
150	15	D	10	C	15 5	CM B	5	BM
200	15	D	15	CM	15	B	10	BM
300	30	D	15	CM	15	BM	—	—
400	50 15	D C	15	BM	—	—	—	—
600	50 20	D C	15	BM	—	—	—	—
800	30 5	C BM	20	BM	—	—	—	—
1 000	30 5	CM BM	15	AM	—	—	—	—
1 500	15 30	BM CM	15	AM	—	—	—	—

Note.—At 100 primary amps and below, 1 amp secondary windings are recommended.

Fig. 16-8, reproduced from test results, shows the ratio and phase angle errors of some wound and ring type (bar primary) current transformers, so that a comparison may be made. It will be seen how the errors correspond, with the same number of ampere turns in the primary, although the cores in the two types are built differently. The effect of increasing the burden is also seen. The usual range of accuracy is from 120 per cent down to 10 per cent of rated current, although it is possible in certain cases to maintain acceptable accuracy for metering purposes, down to 4 per cent. The accuracies shown in the curves are for 15 VA Class "CM" and cores composed of cold reduced silicon iron are used throughout. By the addition of suitable amounts of a nickel steel alloy (known as Mumetal) accuracies of 15 VA Class "BM" and "AM" can be obtained. Although the range of test results is from 120 per cent to 10 per cent rated current, it should be noted that a continuous overload capacity of 20 per cent is not guaranteed owing to thermal limitations of the windings.

Current transformers used for metering purposes need not maintain their accuracy beyond 120 per cent of normal current; in fact, it is an advantage if magnetic saturation sets in beyond this point because it limits the value of secondary current and, consequently, some protection is afforded to the connected instruments.

In the design of any current transformer, consideration must be given to the heating that will occur in both the primary and secondary windings and in the core. Because current transformers are connected in series with the main circuit, they are subject to the heating effects of the normal current continuously carried, including any overloads, as well as those due to the high currents when short-circuits occur between phases or to earth. It is necessary, therefore, to use conductors for the primary winding which are of a large enough cross-section to pass these currents without excessive heating.

The temperature rise in the primary winding when carrying short-circuit current is limited to 200°C. This rise in temperature will be related to the duration of the overcurrent—assuming that all the heat generated is used to raise the temperature of the copper—and hence, the permissible current densities in the copper of the primary winding will vary inversely with the square root of the time interval. This will be seen upon reference to Table 16 : 4, where the current density for 0·5 secs. is 150 000 amperes per sq. in. and, for 3 seconds, is 61 000 amperes per sq. in.

TABLE 16 : 4
(BASED ON TABLE 10 B.S. 81 : 1936)

Rated time in seconds	Current density in amperes per sq. in.
0·5	150 000
1·0	106 000
2·0	75 000
3·0	61 000

Because no relief from the effects of short-circuit current is obtained until the circuit-breakers open, it is desirable to give a short time rating to current transformers that is equal to the time delay in the protective relays plus the inherent time of operation of the associated breakers. Whilst 0·5 second is appropriate for the great majority of applications, where there are several oil circuit-breakers in series—with an 0·5 second operating time difference between them—a time delay of 3 seconds may be given to the breaker nearest the source of supply. Thus the thermal rating required may be greater than the usual 0·5 second, and an increase in the section of the primary copper would be necessary.

This will mean that the space available for this winding will have to be increased or, if this is impossible, the number of turns will have to be reduced. In order to give a performance equivalent to that of the winding rated at 0·5 second where metering accuracy is concerned a material will have to be chosen for the core which has higher permeability and lower losses.

The other important effect of the short-circuit current upon the current transformer is that of the dynamic forces which are set up between the primary and secondary windings, particularly if the transformers are of the "wound" type. These forces consist of a radial force, tending to burst the primary winding and to compress the secondary winding against the core, and an axial force of repulsion between the two windings; these forces, together, may destroy the coil structure. Unlike the thermal effects, the mechanical forces are independent of the time interval, but are proportional to the maximum or peak value of the current during the first major half cycle occurring after the incidence of the short-circuit, including any asymmetry that may be present. This peak value may reach 2·55 times the r.m.s. symmetrical value (see Chapter V). Although of a transient nature, the forces set up may be very destructive and must be allowed for in the design of the transformer; easement may be obtained in one of two ways—either the primary copper section must be increased or the primary ampere turns reduced and in any case, adequate bracing of the coils is essential.

Note, however, that a reduction in the primary ampere turns requires another change, either in the core section or in the core material, in order to maintain the same performance.

Because of problems such as those discussed, an overcurrent factor for a rated time is assigned by the manufacturer to a particular design. This overcurrent factor is the ratio of the rated short-time current to the rated primary current and thus, if a current transformer of ratio 50/5 amperes is required for use in an 11 kV system where the fault level is 250 MVA, i.e. equivalent to 13 100 amperes r.m.s. symmetrical, then the overcurrent factor required is—

$$\frac{13\,100}{50} = 262$$

Whether such a current transformer is economically possible will depend on the required class of accuracy (in the case of protective current transformers on the rated saturation factor), the rated output necessary and the length of time the fault current has to be carried. Overcurrent factors for wound primary current transformers can vary between 250 and 1 000 for a

time duration of 0·5 second and 100 and 400 if the time is extended to 3 seconds. It may be noted that the higher the rated output, accuracy and time, the more difficult and costly becomes the transformer.

B.S. 81 recommends that if an overcurrent factor exceeding 400 for 0·5 second is required, then a bar primary transformer should be used if at all possible. In this type the primary is a single straight conductor and therefore constitutes a single turn so that the primary ampere-turns are always equal to the primary current.

Some typical examples of both wound and bar primary types, including the ring type in which the user provides his own primary conductor, or which can be slipped over busbars or conductors, are shown in Figs. 16-9 to 16-13.

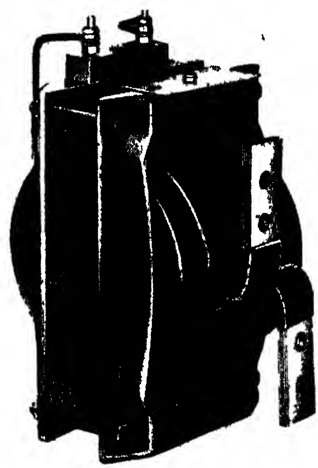


FIG. 16-9.—*Wound primary type of air-cooled current transformer for 3·3 kV service voltage (Johnson & Phillips Ltd.).*

If the secondary winding of a current transformer is open-circuited while normal current is flowing in the primary, a very high and dangerous voltage may be induced in the secondary and the core may overheat. In addition, the magnetic characteristics of the core can be changed such as to affect the accuracy of the transformer.

FIG. 16-10.—*Wound primary type cast resin current transformer for voltages up to 11 kV (Johnson & Phillips Ltd.).*

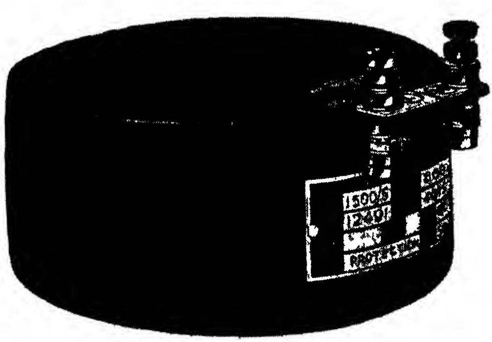


FIG. 16-11.—*Ring type current transformer for voltages up to 660 volts without primary or primary insulation (Johnson & Phillips Ltd.).*

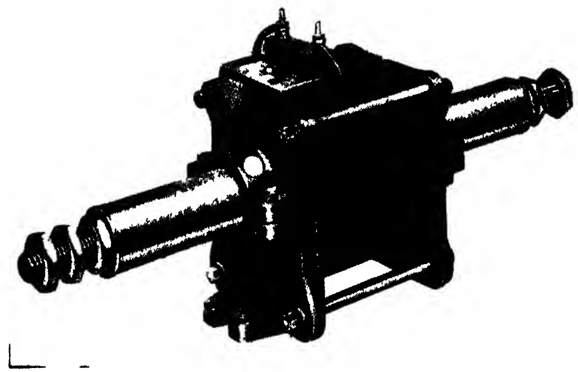


FIG 16-12 —*Bar primary type current transformer with bushing for insulator (plain or condenser), service voltage up to 33 kV (Johnson & Phillips Ltd)*

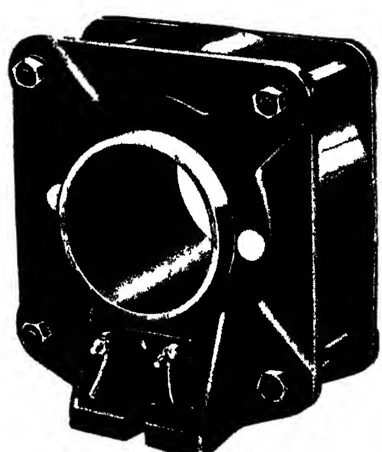


FIG. 16-13.—*Ring type current transformer fitted with clamps and synthetic resin-bonded paper tube (Johnson & Phillips Ltd)*

Voltage transformers

The use of voltage transformers on high-voltage systems for indication and metering is an obvious and necessary corollary to the use of current transformers, and the same basic considerations apply. The transformation must be effected with minimum loss of ratio and divergence in phase angle, (see Table 16 : 5) whilst attaining a high level of insulation between the windings. The design must be as compact as possible to economise in space

TABLE 16 : 5

LIMITS OF ERROR

(SEE CLAUSE 24–B.S. 81 : 1936)

Class	Unity P.F. burden		0·2 P.F. burden	
	At 90–100% of rated voltage and 25–100% of rated burden		At 90–106% of rated voltage and 10–50% of rated burden	
	Ratio error + or − %	Phase error + or − mins.	Ratio error + or − %	Phase error + or − mins.
A	0·5	20	0·5	40
B	1·0	30	1·0	70
C	2·0	60	—	—
D	5·0	—	—	—

and material, and it must be adapted to the particular needs of the switchgear. If required for certain types of gear, the voltage transformer will be usually of the upright and stationary pattern whereas for other types the drawout pattern with interlocks may be required; examples of the two types are shown in Figs. 16-14, 16-15 and 16-16. Outdoor and high-voltage gear will also need special consideration, and some restriction may be placed on the volume of oil used in order to minimise the fire hazard involved.

Oil immersion of the windings is usual for voltages of 6·6 kV and upwards and may even be employed for voltages as low as 2·2 kV in cases where the output exceeds 50 VA per phase and three phase transformation is required Single phase units are often employed for voltages up to 2·2 or 3·3 kV and above 22 or 33 kV and, in the case of very high voltages, they may be of the dry type, using the cascade or capacitor principle of voltage measurement. For voltages up to 660 volts an air-insulated transformer can be used and for 3 300 volt service, a compound-filled design is ideal. These two types are shown in Figs. 16-17 and 16-18.

The performance of voltage transformers is considered more closely today because of the improved accuracy that it is possible to obtain from current transformers; it is the combined accuracy that decides the overall

efficiency of the metering. High accuracy is more easily obtained with the use of core plates of silicon iron than is the case with current transformers, and the restrictions of space are not so severe. Also, an output of 100 or 200 VA per phase at Class "A" or "B" accuracy for voltages up to 11 kV is quite a common performance. The usual connection of the windings is star/star, with the low-voltage neutral point brought out to a separately insulated terminal for earthing if required.

Owing to the high impedance of the windings, it is possible to short-circuit the secondary winding and yet not demand sufficient current from the source of supply on the high-voltage side to melt or "blow" the primary fuses; although it is possible to use very fine wires for these fuse elements, trouble would arise due to the fragile nature of the wires employed, possibly leading to rupture upon shock or mechanical vibration.

It is usual, therefore, to use larger wires which will not deteriorate in service, and to incorporate small low-resistance fuses on the secondary side to deal with overloads or short-circuits. It will of course, be realised that without some protection of this kind, the windings could pass sufficient current to burn themselves out on the high-voltage side, if not on the low-voltage side.

The primary fuses must be regarded, therefore, as only affording protection to the system, that is, for short-circuits or earth-faults in the high-voltage winding. They are usually of the special high rupturing capacity type, the low ohmic resistance of which does not affect the ratio and phase angle errors unduly.

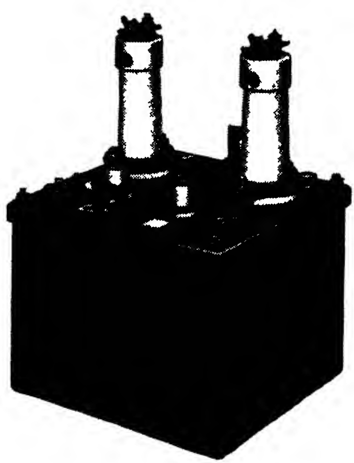


FIG. 16-14.—*Single phase stationary type oil-immersed voltage transformer (Johnson & Phillips Ltd.).*

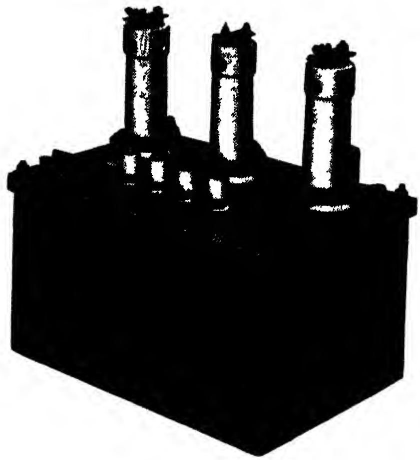


FIG. 16-15.—*Three phase stationary type oil-immersed voltage transformer (Johnson & Phillips Ltd.).*

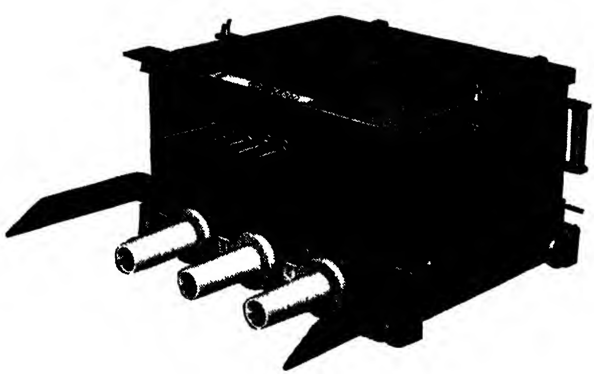


FIG. 16-16.—*Three phase draw-out type oil-immersed voltage transformer (Johnson & Phillips Ltd.).*

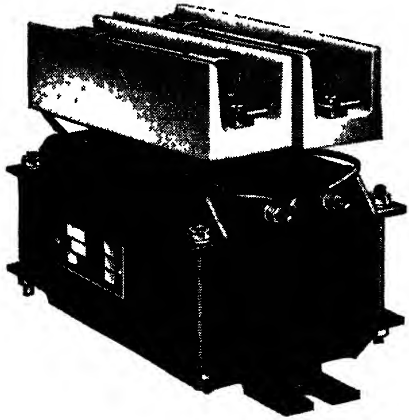


FIG. 16-17.—*Air-insulated voltage transformer for use up to 660 volts (Johnson & Phillips Ltd.).*

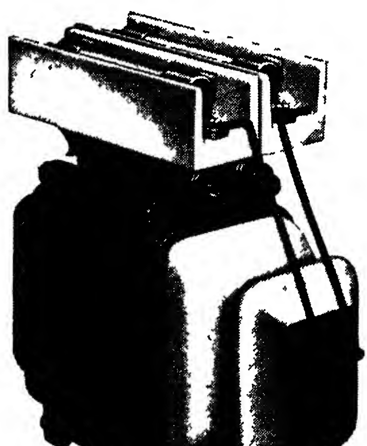


FIG. 16-18.—*Compound-filled voltage transformer up to 3 300/4 400 volts (Johnson & Phillips Ltd.).*

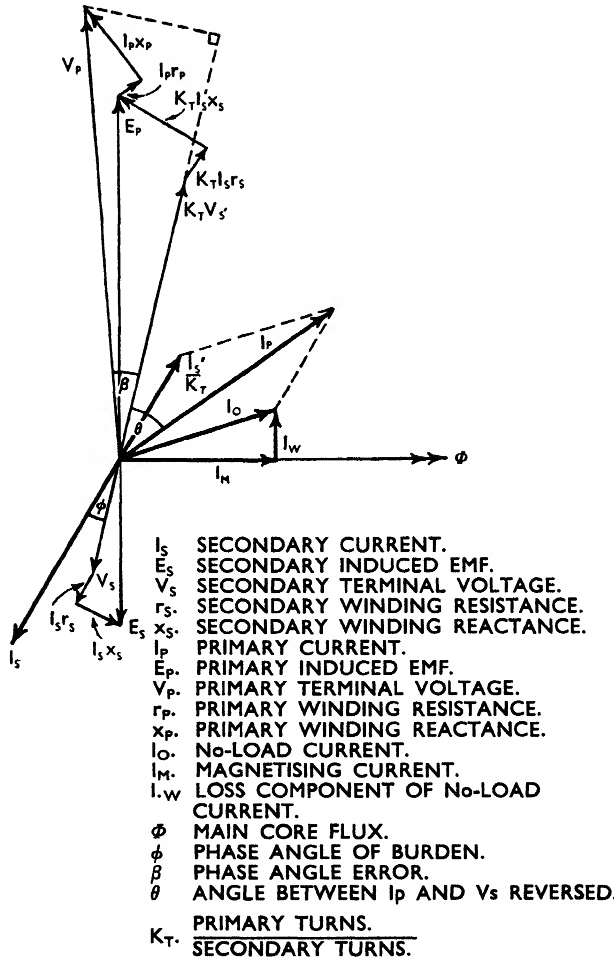


FIG. 16-19.—*Vector diagram for a voltage transformer (not to scale).*

The general principles of power transformer design also apply to the voltage transformer, but there are certain considerations of performance which are of particular importance. To comply with the requirements of B.S. 81, the ratio and phase angle errors at unity and 0·2 power factors of the connected burdens (on secondary side) are limited according to the grade of accuracy specified (see Table 16 : 5) and these limitations will largely determine the permissible watt-loss and magnetising currents. The general effect of these requirements is that the normal flux density permissible in the core is lower than the value generally used in power transformers. This leads to an increase in the dimensions of the core and windings. The turns ratio and voltage drop due to the resistance and reactance of these windings must be carefully determined, in order that the permissible errors will not be exceeded.

It will be of interest to consider the vector diagram of a voltage transformer operating upon a secondary burden with a lagging power factor.

Referring to Fig. 16-19, the secondary terminal voltage V_S is produced from the induced secondary e.m.f. E_S after subtracting, vectorially, the resistive and reactive drops (I_Sr_S and I_Sx_S) occurring in the secondary winding, I_S lagging V_S by the phase angle of the burden ϕ.

The primary induced e.m.f. E_P, which is in opposition to the secondary induced e.m.f. E_S is derived from the applied voltage V_P after supplying resistive and reactive drops caused by both load and excitation currents. The phase angle of the transformer is the angle β between the reversed secondary voltage $K_T\,V_S'$ and the primary voltage V_P and is regarded as having a positive sign when the reversed secondary voltage vector is in advance of the primary voltage vector (anti-clockwise rotation of vectors).

In order to derive equations for the errors of the voltage transformer, it is necessary to refer all the quantities to one side, usually the primary. The secondary drops can be transferred to the primary by multiplying by the turns ratio (K_T) and adding vectorially to the reversed secondary voltage and an expression for the errors can be derived by resolving all quantities along the $K_T\,V_S$ axis.

(a) *The ratio error*

The ratio error is defined in B.S. 81 : 1936 as:—

$$\text{Percentage ratio error} = \frac{K_n\,V_S - V_P}{V_P}\,.100$$

$$\text{where } K_n = \text{Nominal ratio} = \frac{\text{Rated primary voltage}}{\text{Rated secondary voltage}}$$

Resolving along the K_TV_S axis gives:—

$$V_P\cos\beta = K_TV_S + K_TI_Sr_S\cos\phi + K_TI_Sx_S\sin\phi + I_Pr_P\cos\theta + I_Px_P\sin\theta \ldots\ldots(A)$$

Now, in practice β is very small and $\cos\beta \simeq 1$.

Hence K_TV_S is very nearly in phase with E_P

$$\therefore \quad I_P\cos\theta \simeq I_W + \frac{I_S}{K_T}\cos\phi$$

$$\text{and} \quad I_P\sin\theta \simeq I_M + \frac{I_S}{K_T}\sin\phi.$$

Substituting in expression (A) above—

$$V_P \simeq K_T V_S + K_T I_S r_S \cos\phi + K_T I_S x_S \sin\phi + \frac{I_S}{K_T} r_P \cos\phi + \frac{I_S}{K_T} x_P \sin\phi$$
$$+ I_W r_P + I_M x_P$$
$$= K_T V_S + \frac{I_S}{K_T}\cos\phi\,(r_P + K^2_T r_S) + \frac{I_S}{K_T}\sin\phi\,(x_P + K^2_T x_S) + I_W r_P + I_M x_P.$$

But $(r_P + K^2_T r_S)$ is equal to the total resistance referred to the primary winding i.e. $\overline{r_P}$ and $(x_P + K^2_T x_S)$ is equal to the total reactance referred to the primary winding i.e. $\overline{x_P}$

$$\therefore\ V_P = K_T V_S + \frac{I_S}{K_T}\left(\overline{r_P}\cos\phi + \overline{x_P}\sin\phi\right) + I_W r_P + I_M x_P.$$

$\therefore$ the actual ratio is

$$\frac{V_P}{V_S} = K_T + \frac{\frac{I_S}{K_T}\left(\overline{r_P}\cos\phi + \overline{x_P}\sin\phi\right) + I_W r_P + I_M x_P}{V_S}$$

(b) *Phase angle error*

An expression giving phase angle error of the voltage transformer can also be derived quite readily by studying the vector diagram.

$$\operatorname{Tan}\beta = \frac{\text{Horizontal components of voltages}}{\text{Vertical components of voltages}}$$
$$= \frac{K_T I_S x_S \cos\phi - K_T I_S r_S \sin\phi + I_P x_P \cos\theta - I_P r_P \sin\theta}{K_T V_S + K_T I_S r_S \cos\phi + K_T I_S x_S \sin\phi + I_P r_P \cos\theta + I_P x_P \sin\theta}$$
$$\simeq \frac{K_T I_S x_S \cos\phi - K_T I_S r_S \sin\phi + I_P x_P \cos\theta - I_P r_P \sin\theta}{K_T V_S}$$

All other terms in the denominator are small compared with $K_T V_S$ and can be neglected.

Also since β is small $\tan\beta \simeq \beta$.

Substituting for $I_P \cos\theta$ and $I_P \sin\theta$, as before, gives—

$$\beta = \frac{K_T I_S x_S \cos\phi - K_T I_S r_S \sin\phi + I_W x_P + \frac{I_S x_P}{K_T}\cos\phi - I_M r_P - \frac{I_S r_P}{K_T}\sin\phi}{K_T V_S}$$
$$= \frac{\frac{I_S}{K_T}\cos\phi\,(x_P + K^2_T x_S) - \frac{I_S}{K_T}\sin\phi\,(r_P + K^2_T r_S) + I_W x_P - I_M r_P}{K_T V_S}$$
$$-\beta = \frac{\frac{I_S}{K_T}(\overline{x_P}\cos\phi - \overline{r_P}\sin\phi) + I_W x_P - I_M r_P}{K_T V_S}\ \text{radians}$$

By definition, β as calculated here will be negative since, in the vector diagram, $K_T V_S$ is drawn lagging V_P. For β to be positive—

$$\beta = \frac{\dfrac{I_S}{K_T}\left(\overline{r_P}\sin\phi - \overline{x_P}\cos\phi\right) - I_W x_P + I_M r_P}{K_T V_S}$$

By careful design of the windings, the internal resistance and reactance can be kept to an appropriate magnitude, and the magnetising and loss components of the exciting current required by the core itself may be reduced, so that the overall ratio and phase angle errors are within the specified limits of accuracy.

The ratio and phase angle errors of a voltage transformer may readily be determined with fair accuracy from a circle diagram, such as that shown in Fig. 16-20.

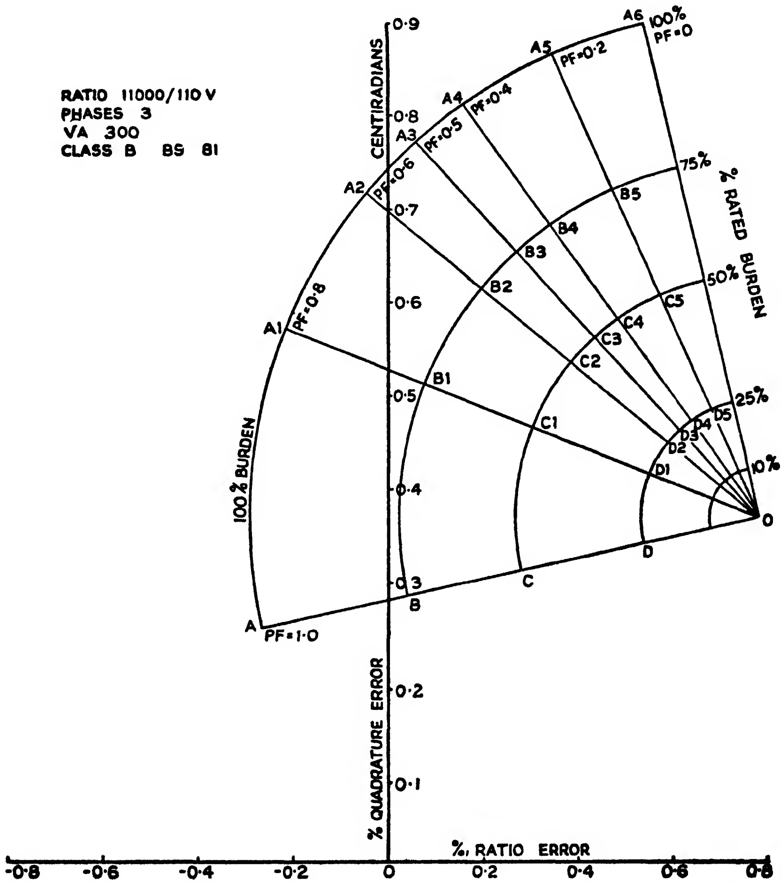


FIG. 16-20.—*Locus diagram for a voltage transformer, showing the effect of burden and power factor on ratio and phase angle error.*

If the load is maintained constant and only the power factor of the burden is varied between zero and unity, the locus of the resultant voltage will be a circle. The impedance drop remains constant in magnitude but alters in position according to the angle of lag of the current. Thus, in the diagram, the points OA, OA_1, OA_2, etc. lie on the circumference of a circle whose centre is at O and whose radius is equal (in scale) to the impedance drop of the transformer.

To construct the diagram, it is sufficient to calculate and plot the values of ratio error and phase angle error at no load and at 100 per cent load at unity power factor. These give points, O and A, on the graph, the horizontal axis representing the percentage ratio error and the vertical axis representing the phase angle error, expressed either as a percentage or in centiradians to scale.

The line, OA_6, may be drawn at right angles to OA to represent the position of the voltage drop at zero power factor. The locus is now drawn between OA and OA_6 and the errors at any other power factor may then be ascertained directly from the graph by choosing a point on the circle representing the power factor required. The errors for intermediate burdens may also be read from the graph by choosing a radius corresponding, in the scale used, to the magnitude of the burden; e.g., OD represents 25 per cent burden, as it is drawn at 0·25 of full radius, OA.

BIBLIOGRAPHY

B.S. 89. Indicating Ammeters, Voltmeters, Wattmeters, Frequency and Power Factor Meter.

B.S. 90. Graphic (recording or chart recording) Ammeters, Voltmeter Wattmeters, Power Factor and Frequency Meters.

B.S. 81. Instrument Transformers.

Power Wiring Diagrams, A. T. Dover (Sir Isaac Pitman & Sons).

Switchgear Practice, A. Arnold (Chapman & Hall).

Instrument Transformers, B. Hague (Pitman and Sons, Ltd.).

"INSTRUMENT TRANSFORMERS," J. G. Wellings, "B.T.H. Activities," May, 1936.

"INSTRUMENT TRANSFORMERS," J. G. Wellings and C. G. Mayo," "Journal I.E.E.", Vol. 68, 1930.

"INSTRUMENT TRANSFORMERS," A. Hobson, "Journal I.E.E.", Vol. 91, Part II, No. 20, April, 1944.

CHAPTER XVII
CONTROL BOARDS

CHAPTER XVII

CONTROL BOARDS

THE remote control of power switchgear requires the provision of suitable control panels located at a point removed from the immediate vicinity of the circuit-breakers and other apparatus. Preferably, the location should be a room set apart for the purpose and in a place of relative seclusion away from noise and other causes of distraction, freedom from the latter being particularly important at times of emergency.

Not only will the remote control board carry the appropriate means whereby the circuit-breakers may be opened or closed but also any necessary indicating, integrating or recording instruments, indicating lamps or semaphores to denote the open or closed state of circuit-breakers and isolating switches, protective relays, control circuit and other secondary fuses and, in some instances, voltage regulating equipment.

In this chapter we shall be concerned only with remote control where the distance between the control board and the switchgear and other electrical apparatus is such as to permit direct wiring between the various items. Such conditions normally exist in power stations, most indoor and some outdoor substations, and in large industrial undertakings. When remote control is required for an extensive distribution or transmission system where long distances are involved between the control point and the controlled switchgear, the centralised control equipment will be of a very different type in order to avoid the prohibitive cost of heavy control cables of long length. In these circumstances, telecommunication engineering is called upon to provide remote control which employs supervisory equipment of the automatic telephone type. In this respect, a large power network may be compared with a telephone communication system in that in the latter a coded signal initiated by a caller selects the remote subscriber to whom he wishes to speak, while in a power network the control engineer sends out a coded signal to select and operate a chosen circuit-breaker. There is, however, an important difference, namely that whereas wrong coding or numbers when telephoning are simply inconvenient, any inaccuracy when controlling switching operations could have disastrous results and, therefore, elaborate check-back precautions are necessary. How these are achieved and how many other problems associated with remote supervisory control are solved, are, however, beyond the scope of this chapter.

The layout of any particular control board and/or relay board will depend to a large extent on the size of the system to be controlled, on operational requirements and on the users' preferences.

When a large number of circuits are to be controlled, as for example in a major power station, it is important that the indicating apparatus should be clearly visible from a control position and that the controls be arranged for easy operation. It may be necessary to incorporate in the control board a mimic diagram representing the main circuit connections with automatic semaphore indicators to denote the state of the system. It may be advantageous to provide alarm indication equipment which will give both audible and visual indication to the control engineer of any change, e.g. the operation

of protective devices, where the fault lies and what tripping of circuit-breakers has occurred

If the system is such as to require a large number of protective relays, metering equipment and other apparatus not under constant watch, then it is preferable that all such apparatus be removed from the main control board and be placed on a separate relay and metering board In many cases, the main control board and the relay board can be arranged back-to back to give a corridor formation In power stations, it is often convenient, for ease of operation, to include the control equipment for the generators (and perhaps, main transformers) on a separate control desk located in front of the main control board

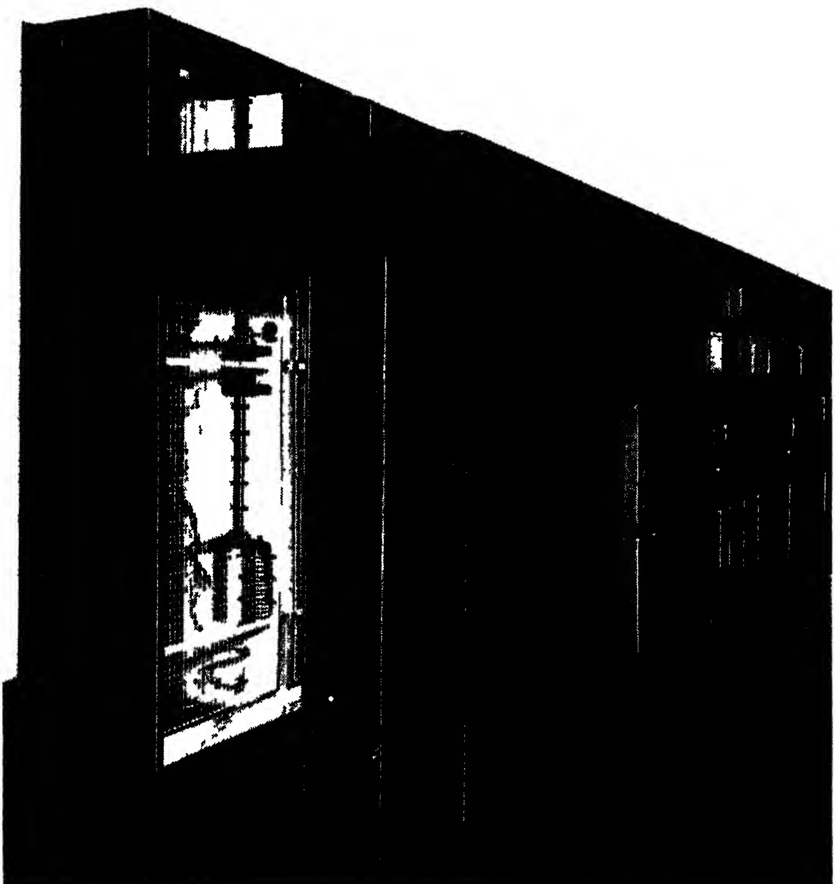


FIG 17-1 —*Illustrating the construction of a corridor type control and relay board (A Reyrolle & Co Ltd)*

For medium sized installations, where the number of controlled circuits is small and there are no elaborate forms of protective gear, a much simpler control board will meet the requirements, any relays or metering equipment being combined on the one board along with the control switches.

In general, control or relay boards will be built up by using the requisite number of self-contained sheet-steel cubicles comprising a fixed front panel to carry the control apparatus and a hinged or removable back cover to give

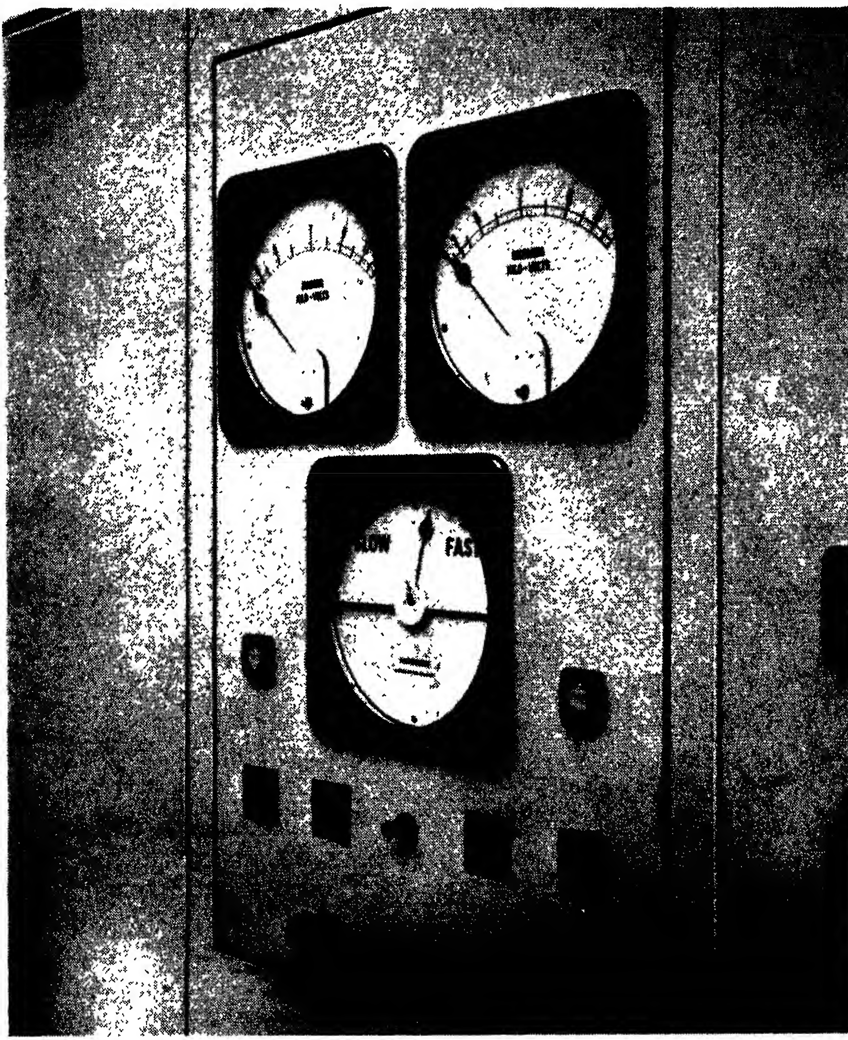


FIG. 17-2.—*Hinged synchronising panel in the run of a control board (A Reyrolle & Co. Ltd.).*

access to the interior wiring, cable terminations, etc. Each cubicle will be fitted with a lamp which will automatically be switched on when the rear door is opened. When control panels and relay panels are arranged back-to-back in corridor formation, the rear access door may be replaced by wire mesh screens, and a door will then be fitted at each end of the corridor. The latter will be illuminated automatically when either corridor door is opened. An example of a typical arrangement of this kind is shown in Fig. 17-1, the illustration showing the rear view. It also shows how a wiring trough between the control and relay boards is used to carry the interconnecting wiring and to roof in the corridor.

In the majority of designs, the appearance of the main control board is enhanced by maintaining a flush, or nearly flush, front, and to this end any indicating instruments should be of the flush mounting type. Where relays are not mounted on a separate board, these too should be of the flush type.

There are many possible variations for the accommodation of synchronising instruments as required for generating stations. These include hinged panels mounted in the run of the control board, hinged box panels at the end of the board, floor mounted pedestals, or a portable trolley with a flexible lead for plugging into a socket on the panel controlling the circuit to be synchronised. Examples of such arrangements are noted in Figs. 17-2 to 17-6.

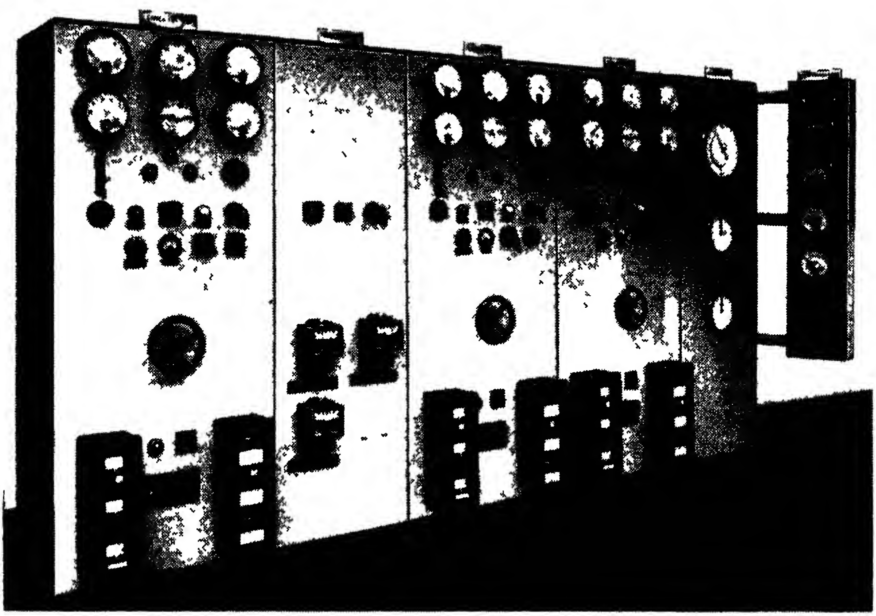


FIG. 17-3.—*Hinged synchronising panel at end of control board (Johnson & Phillips Ltd.).*

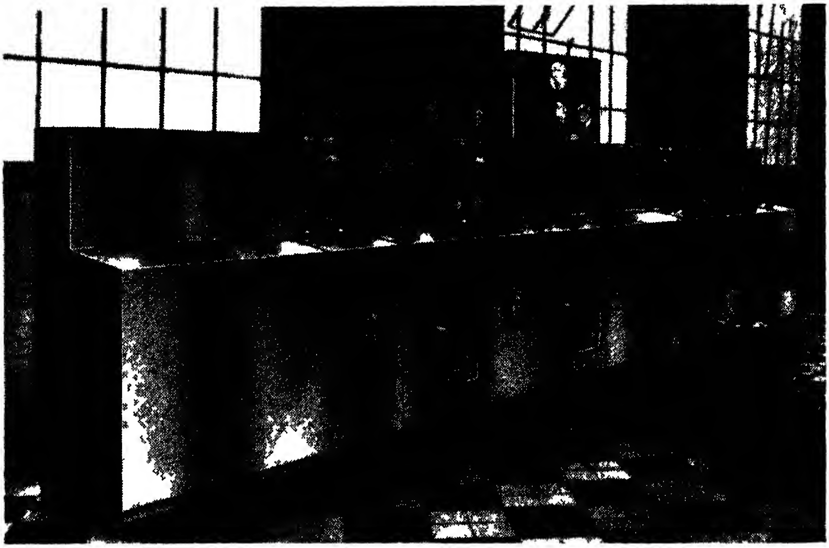


Fig 17-4 —*Hinged synchronising panel surmounting a control desk (Johnson & Phillips Ltd)*

Fig 17-5 —*Swivelling synchronising panel on pedestal (Johnson & Phillips Ltd)*

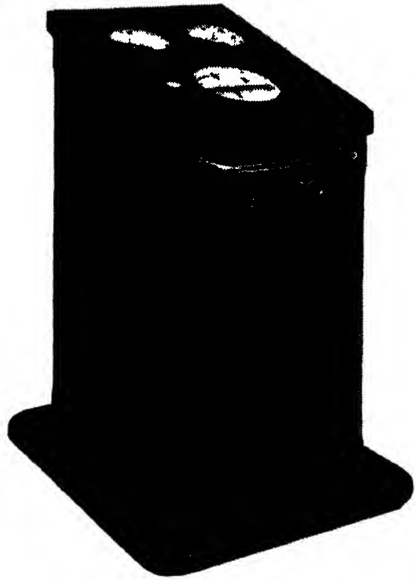


FIG 17-6 —*Portable synchronising trolley for plugging in to circuit being synchronised (A Reyrolle & Co Ltd)*

When a mimic diagram is required, this may be incorporated on the front panels of the control board or may be displayed on separate auxiliary cubicles mounted above the main board The automatic semaphore indicator

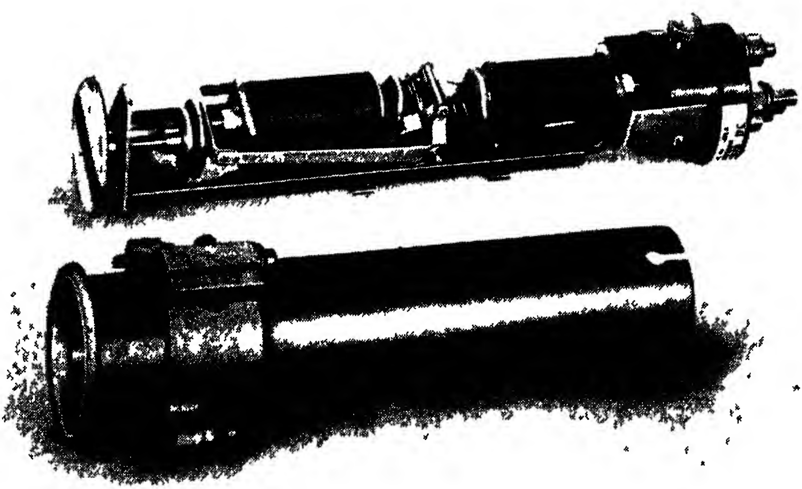


FIG. 17-7.—*Automatic semaphore indicator for use in mimic diagrams Cover removed (The English Electric Co Ltd)*

used in many mimic diagrams is illustrated in Fig. 17-7, the flat disc being inscribed with a coloured stripe on a white background to form part of the diagram as shown in the typical circuit, Fig. 17-8.

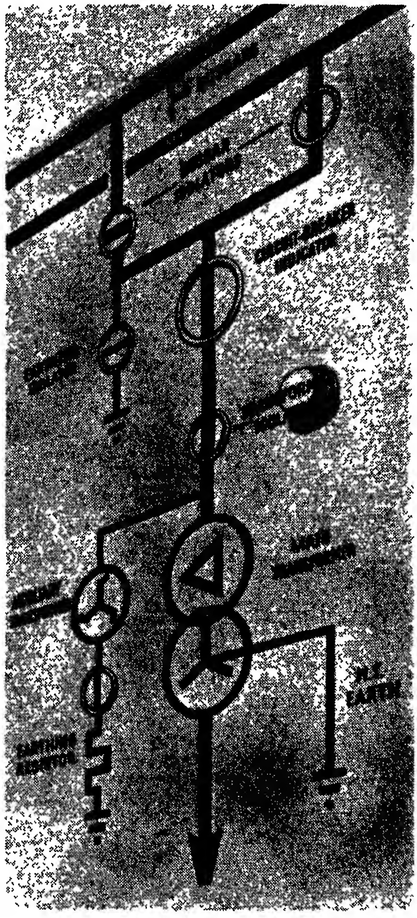


FIG. 17-8.—*An example of a mimic circuit diagram panel using automatic semaphore indicators (The English Electric Co. Ltd.).*

Note.—The references on this illustration have been added for information and do not appear on the control board itself.

The operating impulse is derived from a separate source of supply, a.c., or d.c., *via* auxiliary contacts on the associated circuit-breaker or switch. Indicators may be in various sizes, the normal having $1\frac{1}{2}$ or 2 inch diameter discs. They can be of the latch-in type which will maintain the last indicated position when the supply fails, or a supply-failure type which will give an

indication of such failure, the disc moving to a 45° neutral position or single coil type in which the disc is spring-returned to its original position when the coil is de-energised.

Alternatively, the handle of the control switch can take the form of a semaphore indicator, the control switch now being mounted in the run of the mimic diagram. In this case it will be clear that, being hand operated, the control switch semaphore may give a false indication should the circuit-breaker be "tripped open" by the protective gear, the semaphore still indicating "closed". To overcome the danger inherent in such circumstances, a discrepancy lamp is incorporated in the control switch assembly and this lights up automatically when any discrepancy occurs, either as described above or in the converse case when the semaphore on the control switch indicates that the circuit-breaker is open but in fact it has been closed by local control at the breaker. A typical combined control switch and semaphore indicator with discrepancy lamp is shown in Fig. 17-9.

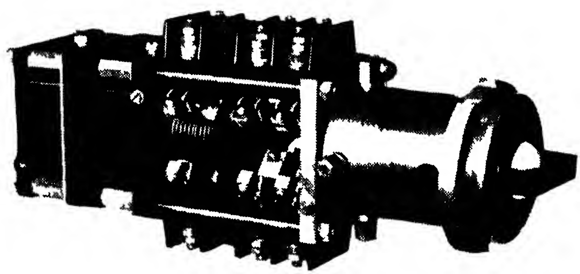


FIG. 17-9.—*Combined control switch and semaphore indicator with discrepancy lamp (The General Electric Co. Ltd.).*

Circuit-breaker control switches are generally fitted with what is known as a pistol grip handle as shown in Fig. 17-10.

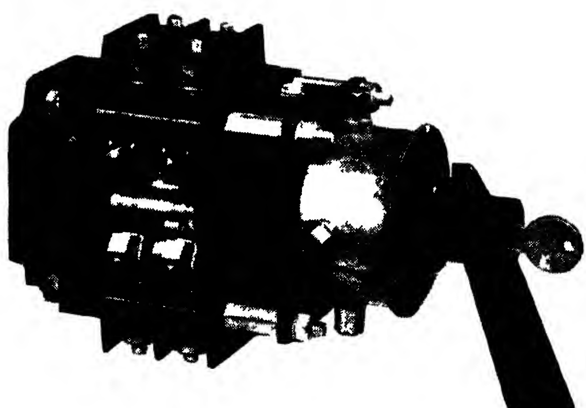


FIG. 17-10.—*Circuit-breaker control switch with pistol grip handle and key lock in neutral position (The General Electric Co. Ltd.).*

They are normally of the spring return to neutral type, the handle being moved to the right or the left to initiate the "close" or "trip" operations. A sequence interlock ensures that it is impossible to perform two closing operations successively. Switches may include additional contact assemblies over and above those required for circuit-breaker control and these may be used for a number of purposes, e.g. energising an alarm circuit in the event of a circuit-breaker tripping automatically under fault conditions.

Indicating lamps may be used for a variety of purposes on control boards and these follow a standard colour code as below.

Red — Circuit-breaker or switch closed
Green — Circuit-breaker or switch open
White — Trip supply healthy
Amber — Alarm indication, e.g. circuit-breaker tripped on fault

The source of supply for these lamps is usually that used for normal lighting purposes in the control room, i.e. 230/250 volts. As it is only necessary to give sufficient illumination to ensure a positive indication, the lamps are usually of the 15 watt pigmy type but even so the heat to be dissipated in a small and relatively enclosed fitting can sometimes be a problem. To overcome this and at the same time reduce the panel face dimensions, indicating lamps are available which have a small single phase step-down transformer built in to the assembly as shown in Fig. 17-11.

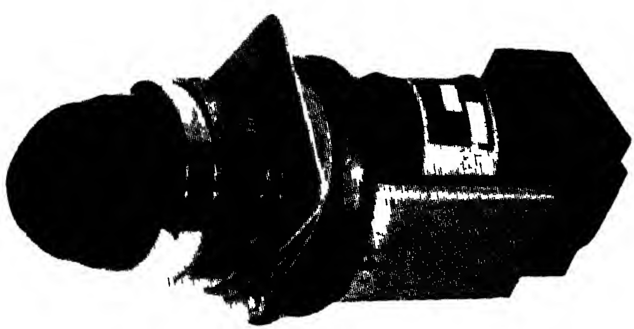


FIG. 17-11.—*Control board indicating lamp with built-in step-down transformer (Everett Edgcumbe & Co. Ltd.).*

In this design, the output voltage to the lamp is 12 volts and the lamp itself is a miniature bayonet socket type with a consumption of only 2·2 watts, thus ensuring an extremely long life.

Similarly, fuse and link assemblies in the control and other circuits should be coloured for identification, the accepted standard being black for 5 ampere fuses, green for 15 ampere fuses, and white for links.

An essential feature of all control and relay boards is an orderly assembly of small wiring. This is necessary to facilitate checking in the event of trouble and to further assist in this, all wiring should be numbered to correspond with a circuit diagram of connections. This is usually achieved by means of engraved ferrules fitted to the ends of the wires. The numbers

should be repeated on terminal studs so that if a wire is removed at any time, there can be no doubt as to its point of reconnection.

Terminal boards are not always easy of access but they can be made so by mounting them at an angle of 45°. This is of importance when a number of terminal boards must be used and they are mounted one behind the other.

Typical of an orderly scheme of wiring and terminal blocks is that shown in Fig. 17-12.

FIG. 17-12.—*Rear view of busbar protection relay panels showing small wiring and angled terminal blocks (Johnson & Phillips Ltd.).*

We have noted earlier that in some circumstances and particularly on large, interconnected networks, it is advantageous to provide at the control point some form of alarm indication. This usually is an annunciator scheme using illuminated facias with engraved legends to indicate the position of, or type of fault on, remotely situated equipment. Such a scheme is of considerable assistance to control engineers in assessing quickly the extent of system disturbance and to minimise the delay in taking remedial action. Initiation of the alarm and visual indication is usually through contacts on the protective relays or on a moving member of the equipment under surveillance, causing the following sequence of events:—

(1) An alarm bell rings and the appropriate facia alarm lamp flashes on and off to attract attention.
(2) The control engineer "accepts" the signal by pressing a button, which silences the bell and causes the lamp to show a steady light.
(3) After taking remedial action, and logging the cause, the control engineer "resets" the alarm circuit by pressing another button, the lamp being simultaneously extinguished.

In the past, most annunication schemes have used telephone type relays having numerous contacts requiring periodical maintenance. In a recent development, however, transistors have replaced the relays and, being a static component, the need for maintenance has been eliminated.

A scheme of this type is shown in Fig. 17-13, which is a typical block schematic diagram for a single alarm channel, the transistorised switching units being indicated A, B, C and D.

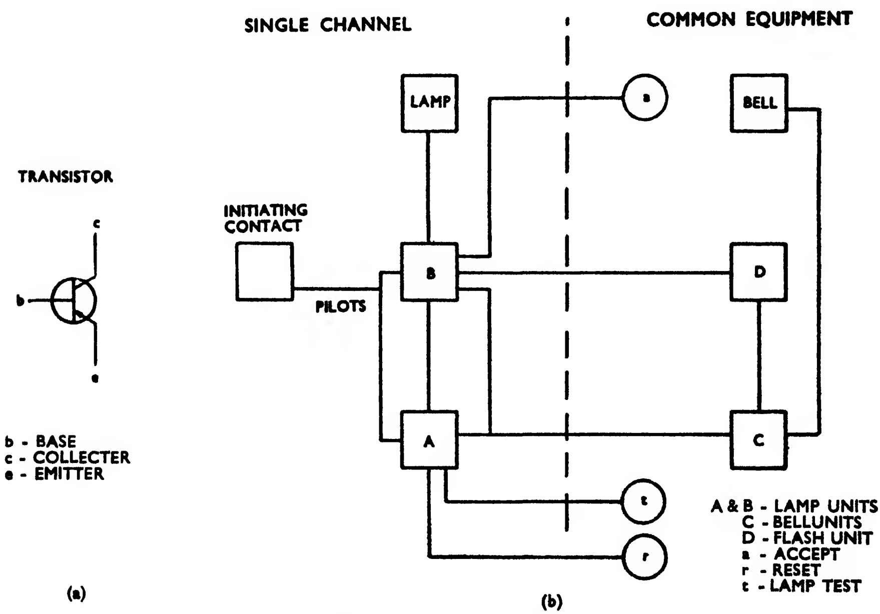


FIG. 17-13.—*Transistor alarm annunciator scheme (A. Reyrolle & Co. Ltd.).*

The transistors may be compared to the contacts on a relay, i.e., when the transistor is conducting (ON) it is equal to a pair of closed contacts and when not conducting (OFF) to a pair of open contacts. The transistor is basically a three terminal device (see diagram (a), Fig. 17-13) and is switched on or off by the polarity appearing at the base relative to that at the emitter. In the arrangement shown, a negative potential applied to the base relative to the emitter will switch the transistor on, i.e., the collector-emitter path will have a low impedance. Conversely a positive potential applied to the base relative to the emitter, will switch the transistor off, i.e., the collector-emitter path will become one of very high impedance.

In the diagram Fig. 17-13 (b) the A and B transistor units control the lamp, the C unit the alarm bell and the D unit the lamp flashing sequence. The input to the A and B units are the initiating contact, lamp test and reset. The output from A is used to control the output from B, which in turn controls the lamp. When the fault initiating contacts are closed, the A and B units are switched over, which allows the C unit to operate the audible alarm and the D unit to control the lamp flashing sequence.

On pressing the "accept" button (a), the B unit is switched back to its quiescent state thereby switching off the audible alarm via the C unit and

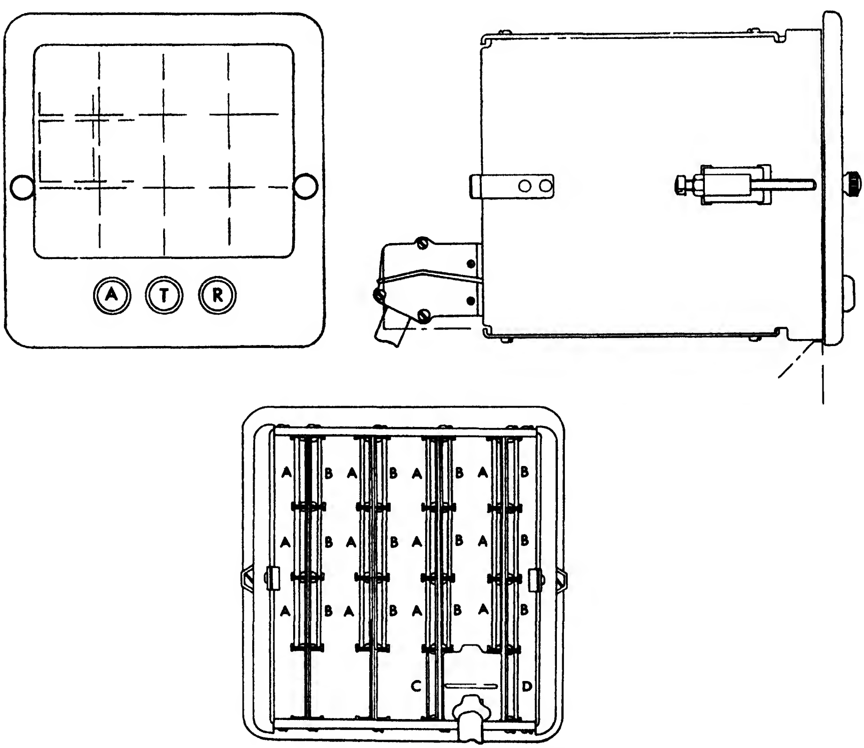


FIG. 17-14.—*Typical 12-way alarm assembly (A. Reyrolle & Co. Ltd.).*

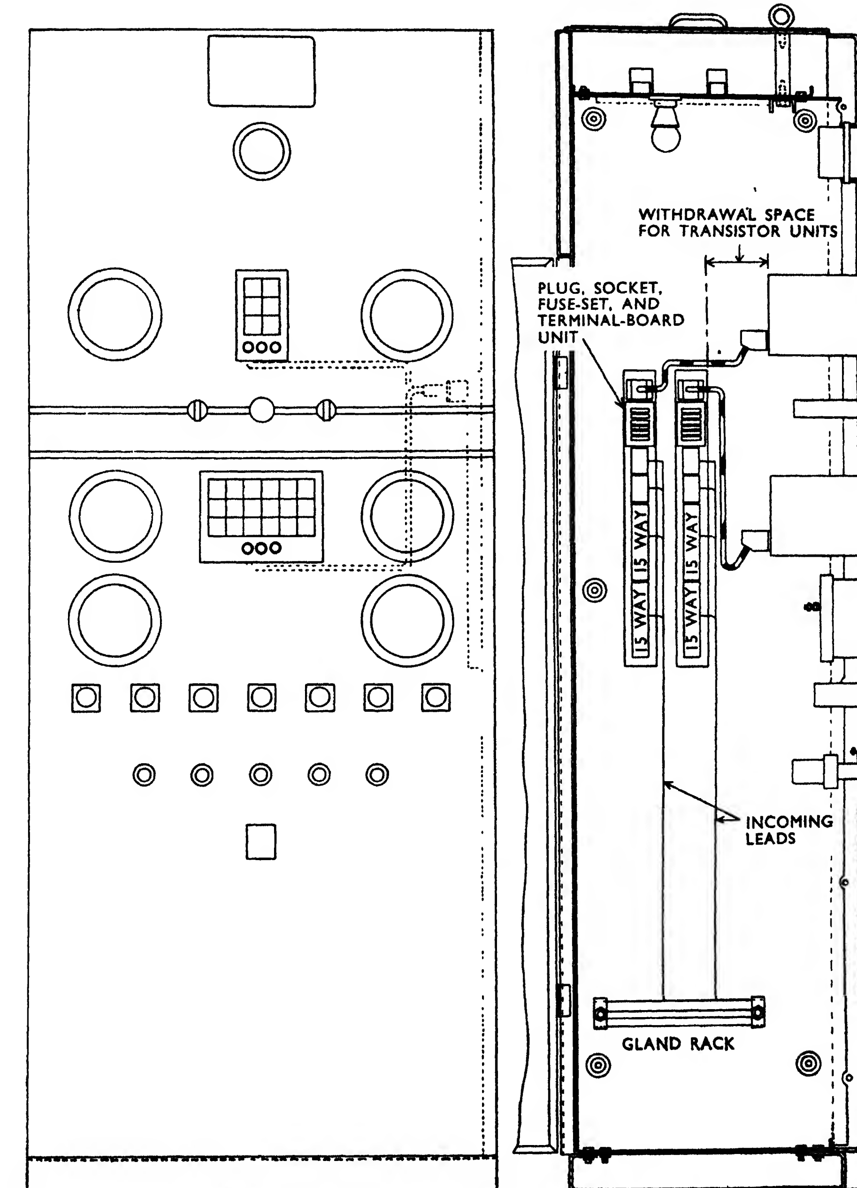


FIG. 17-15.—*Typical control panel with alarm facias (A. Reyrolle & Co. Ltd.).*

the flashing sequence via D, the lamp remaining on but now showing a steady light. Pressing the "reset" button (r) switches the A unit to its quiescent state, thereby extinguishing the lamp by switching off the output from the B unit. From the diagram it is seen that the C and D units and the push buttons are common to a number of channels and can cover up to twenty-four. Provision is made whereby the lamps can be tested at any time by pressing button (t).

The alarm assembly comprises a flush mounting housing which carries the appropriate number of lens boxes. On each of the latter is engraved the required legend and each lens box is illuminated from behind by its own lamp, the legend being seen through a translucent glass panel. Behind each lamp housing are sockets which receive the printed-circuit transistor switching units A and B, while the common transistor units C and D are accommodated behind the three push buttons at the base of the assembly, all as shown in Fig. 17-14.

Facias in this design are available to accommodate from 4 to 144 alarms and the equipment requires a 50 volt d.c. supply for operation.

Fig. 17-15 shows a typical control panel on which are mounted two alarm units, one 18-way, the other 6-way.

In order to illustrate what has been discussed throughout this chapter, the remaining pages will include a representative selection of photographs of completed control and relay boards.

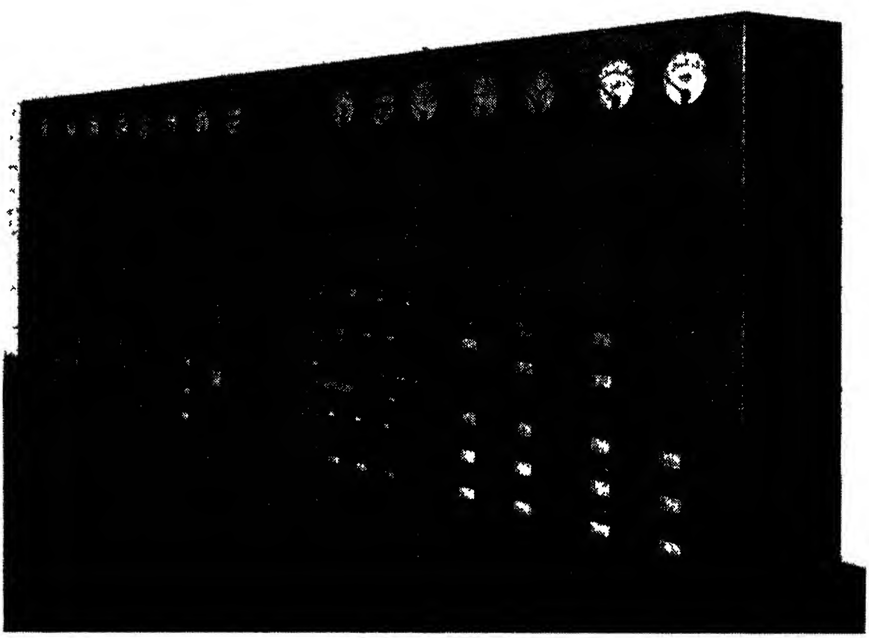


FIG. 17-16.—*Remote control and relay board (Johnson & Phillips Ltd.).*

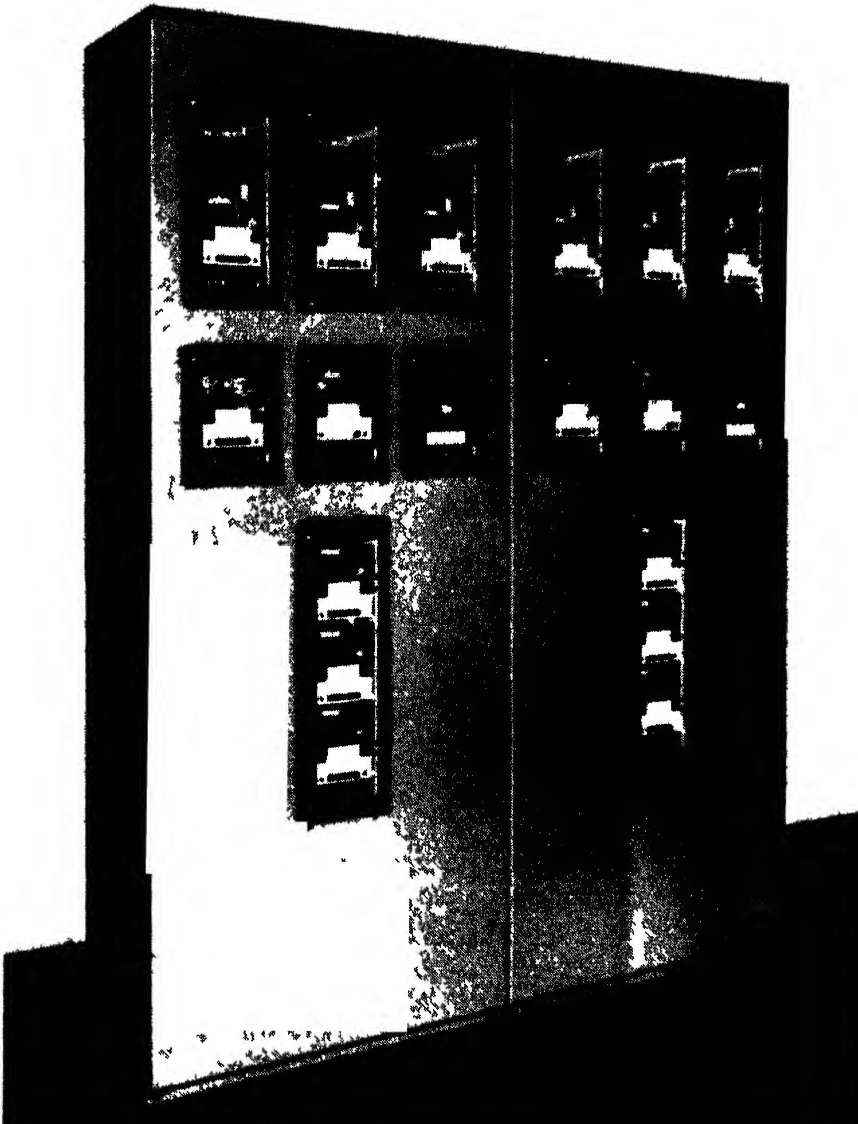


FIG 17-17 —*Separate relay board (Johnson & Phillips Ltd)*

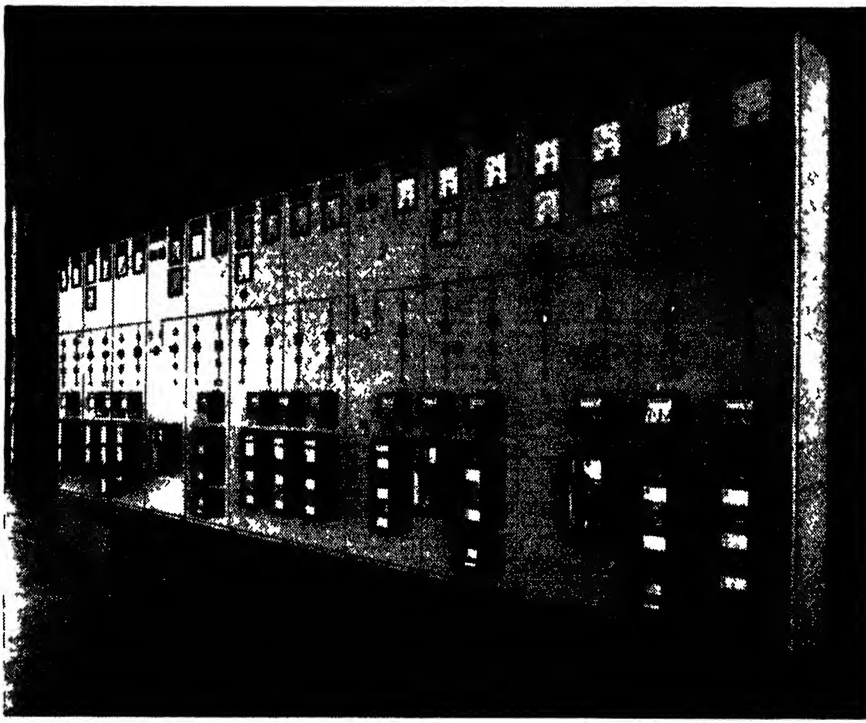


FIG. 17-18.—*Control board with mimic diagram. Each control switch forms the semaphore for a circuit-breaker. National Coal Board, Seafield Colliery (Johnson & Phillips Ltd.)*

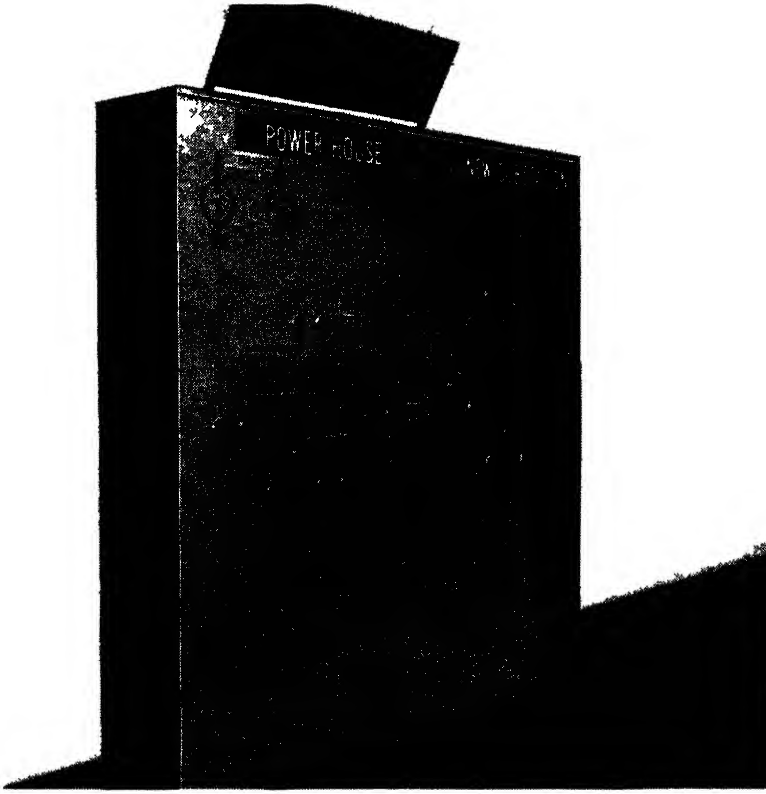


FIG 17-19 —*Separate mimic diagram panels for South-Eastern Gas Board Note that diagrams embrace 6·6 kV and 440 volt a c systems and 220 volt d c (Johnson & Phillips Ltd)*

FIG 17-20 —*Generator control desk for State Electricity Commission of Western Australia (The English Electric Co Ltd)*

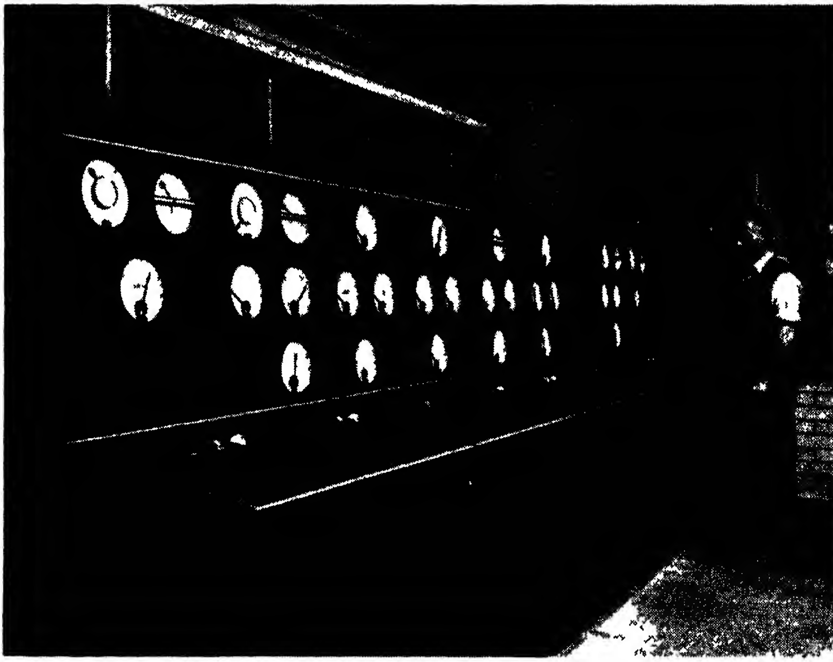


FIG. 17-21.—*Control desk at The National Coal Board, Ollerton Colliery (Johnson & Phillips Ltd.)*

FIG. 17-22.—*Control board and desk in power station. Mimic diagram below the indicating instruments (The English Electric Co. Ltd.).*

FIG 17-23 —*Corridor type control board with relay board at rear Generator control desk in front Mimic diagram above the indicating instruments* (*The English Electric Co Ltd*)

FIG. 17-24 —*Control boards and desks, Keadby Generating Station C E G B.* (*A. Reyrolle & Co Ltd*)

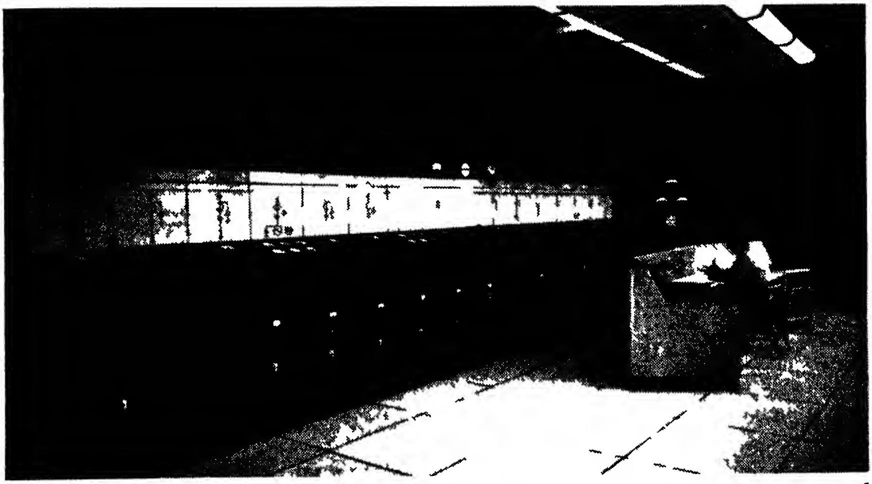


FIG 17-25 —*Control desks in British Enka Ltd generating station Vertical mimic diagram above main desk (A Reyrolle & Co Ltd)*

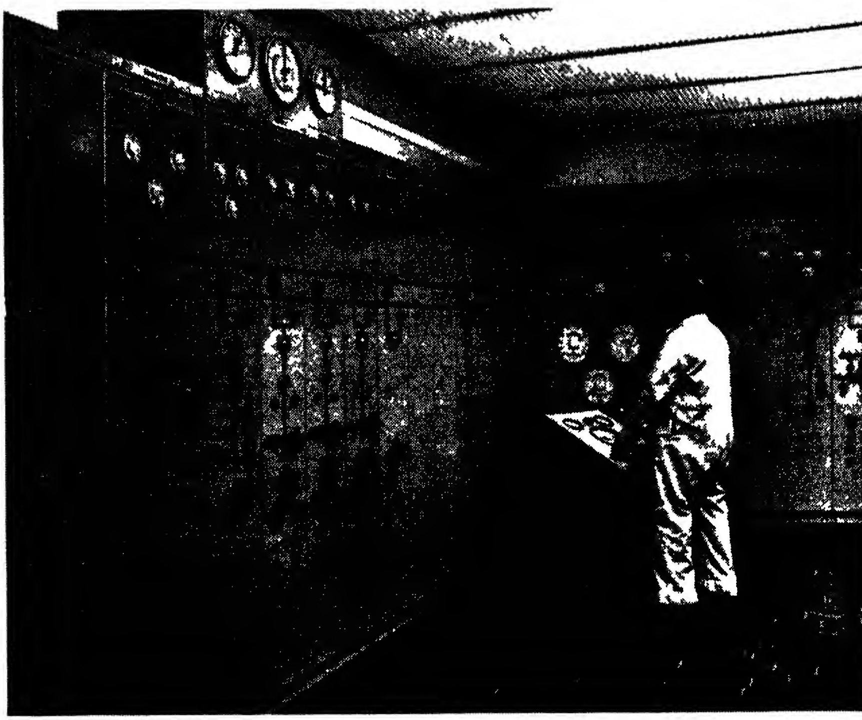


FIG 17-26 —*Part of the 275 kV/132 kV control board at Willington Power Station C E G B Note the portable synchronising equipment in use (The General Electric Co Ltd)*

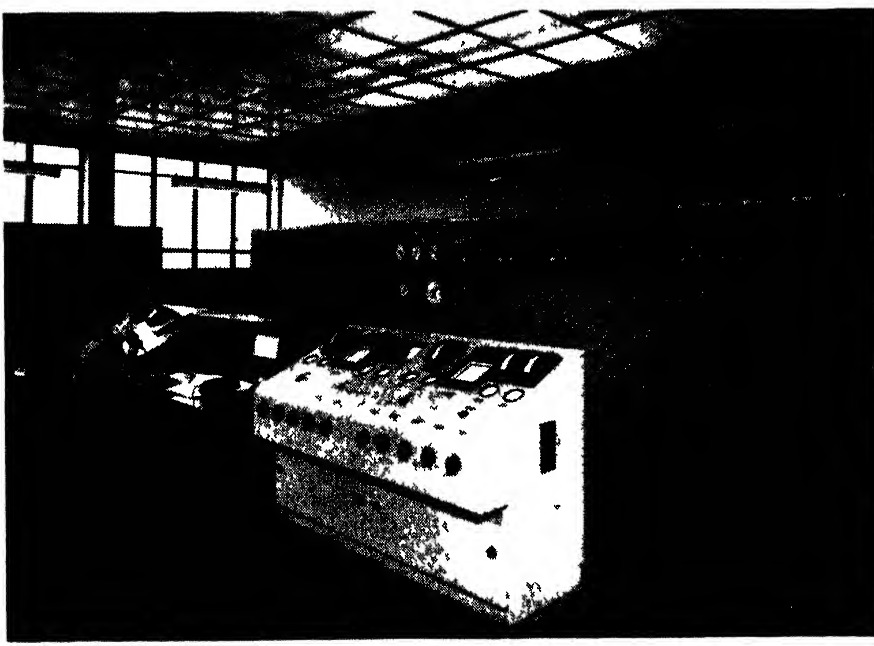


FIG 17-27 —*Control board with mimic diagram below and illuminated fault-indicating units along the top of the board (The General Electric Co Ltd)*

CHAPTER XVIII
OUTDOOR SWITCHGEAR

CHAPTER XVIII

OUTDOOR SWITCHGEAR

For the purpose of this chapter, outdoor switchgear falls broadly into two groups. The first group is that which covers the many types of gear available for the control of electricity supplies at locations relatively remote from the major network and more particularly for rural distribution. The second group is that which includes the larger substations essential in urban distribution and those major switching stations associated with interconnected high-power networks, usually at 66 kV and above.

In both groups, the major economy derives from the fact that the cost of buildings is eliminated. Space is an important factor and this has led in recent years to the use of what are popularly known as packaged substations. In rural distribution particularly, where some 80 per cent of outages are due to faults of a transient nature, there may be a lengthy loss of supply if an engineer has to be sent out to restore the service and therefore considerable thought has been devoted to the problem of automatic restoration.

At the very high voltages, the space taken up is largely determined by the electrical clearances necessary and by the size of the circuit-breakers, which may be of the oil-break, air-blast or small-oil-volume types as described in earlier chapters.

With this brief introduction, it will be convenient to consider the types of gear suitable for various kinds of installation and described under the following headings:—

(a) The high-voltage fuse
(b) Automatic reclosers for rural distribution
(c) The pole-mounting circuit-breaker
(d) Oil-switches
(e) Metal-clad or metal-enclosed (packaged) switchgear
(f) Major switching stations or substations

THE HIGH-VOLTAGE FUSE

B.S. 2692 recognises the existence of several designs of fuse for use on voltages higher than 660 volts, among them being the expulsion fuse, the powder-filled cartridge fuse, the liquid fuse and an oil-tank fuse. Of these we shall only be concerned with the first two, noting in passing that the powder-filled cartridge type is usually of the current-limiting type and must be oil-tight where it is required to be immersed in oil.

An expulsion fuse comprises an open-ended tube, often of synthetic resin-bonded paper, in which the fuse element is contained and which is connected to suitable fittings at each end. The length of break in this type is increased by expulsion of part or all of the fuse-element and the process of arc quenching may be assisted by the movement of the vapour from the containing tube. This vapour may be generated wholly by the volatilization

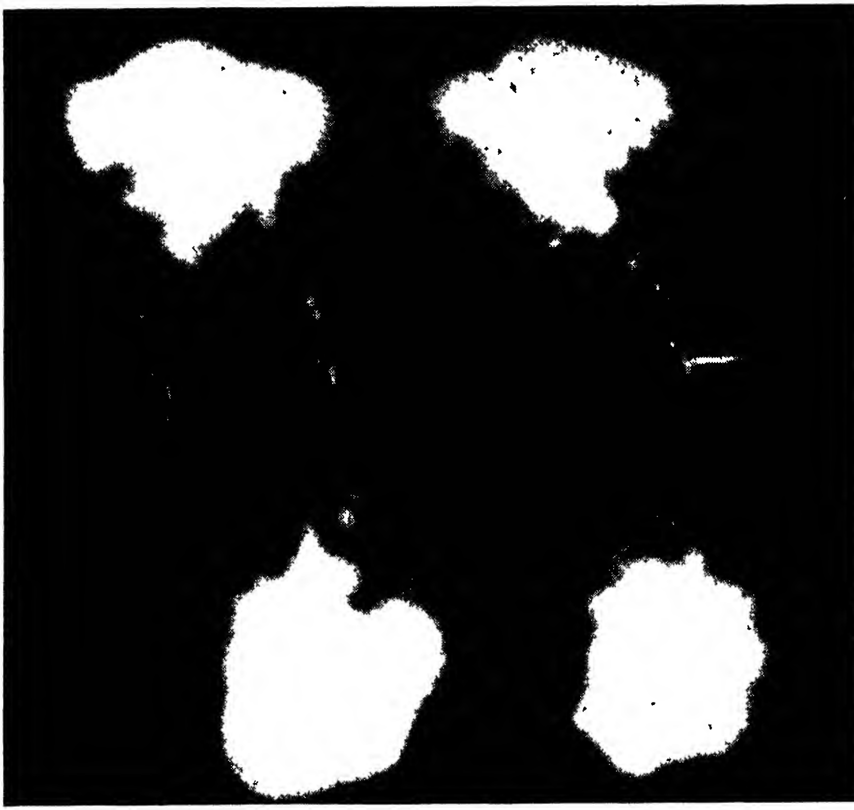


Fig. 18-1.—*Expulsion type fuses clearing a three phase fault of 150 MVA at 11 kV during short-circuit tests. From a high-speed ciné film at 3 000 frames per second (Johnson & Phillips Ltd.).*

of the fuse-element or partly by the effect of heat on a solid substance carried either by the fuse-link or by the inner wall of the tube. Gas expulsion from fuses of this type when clearing a fault of 150 MVA at 11 kV, three phase, is noted in Fig. 18-1. Note that one fuse has been replaced by a solid link, thus, on a three phase test, ensuring that the recovery voltage across the fuses was not less than line to line voltage.

The fuses seen in Fig. 18-1 are effectively fuse-switches as once the fuse element has melted, the tube is free to swing down to an isolated position thereby providing an unmistakable indication that a fuse has operated. The location of the interruption can therefore be easily detected by a linesman. This feature will be clear from Figs. 18-2 and 18-3 which show the fuse-switch in the closed and open positions respectively.

FIG. 18-2.—11 *kV Type 'D' expulsion fuse-switch in closed position (Johnson & Phillips Ltd.).*

FIG. 18-3.—11 *kV Type 'D' expulsion fuse-switch in isolated position (Johnson & Phillips Ltd.).*

The element in this design is connected at each end of the tube to suitable fittings by clamp plates and thumb screws and when intact, the element holds the switch in the latched closed position. Melting of the element releases the latch-in trigger and the tube swings down, the pressure exerted by the multi-line brush type contacts initiating and assisting this movement. These contacts are fitted at both ends of the fuse tube, those at the hinge ensuring that current carrying is independent of the hinge components.

Having located the fuse which has operated, the linesman lifts the complete tube clear of its hinge by means of an insulated operating pole and lowers it to ground level for element replacement, following which the tube

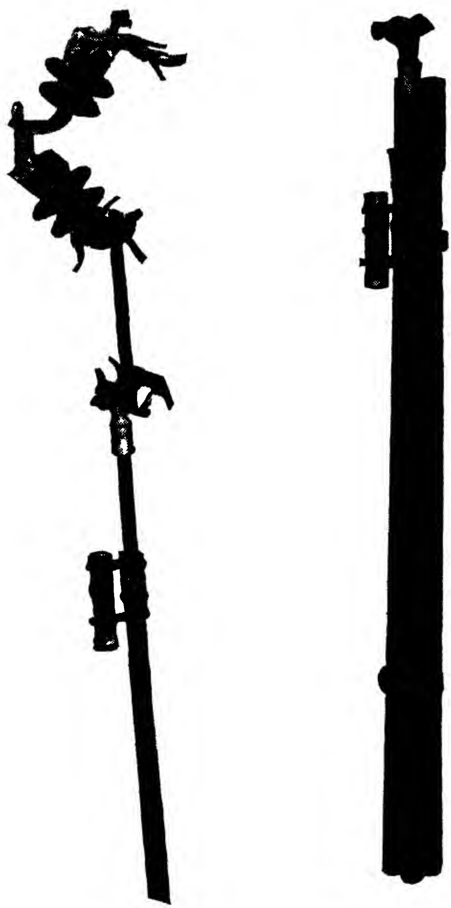


FIG. 18-4.—*Showing at left, the operating pole in use to remove or replace a fuse-switch tube from its hinges. Note the torch for night use—the complete pole assembled for carrying is on the right (Johnson & Phillips Ltd.).*

FIG. 18-5 —*Fuse-switch tube being reclosed after renewal of fuse element (Johnson & Phillips Ltd)*

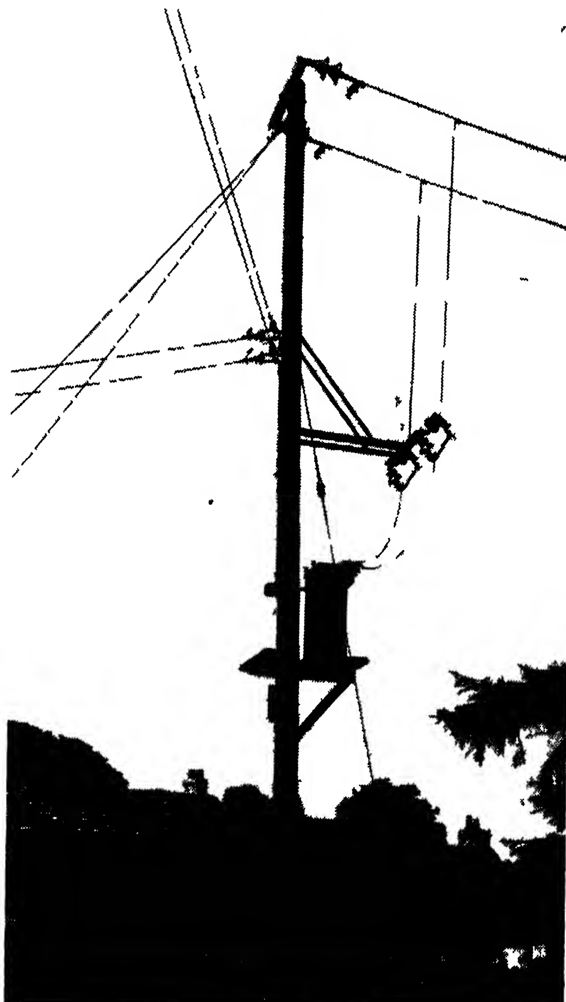


FIG. 18-6—*Type "D" expulsion fuse-switches installed at a single phase pole-mounted transformer substation (Johnson & Phillips Ltd.).*

is replaced in its hinge trunnions and reclosed after the manner of an isolating switch. These operations are illustrated in Figs. 18-4 and 18-5, and it may be noted that in circumstances where a fuse has not operated but it is required to isolate a circuit, the same operating pole can be used to release the trigger latch to permit the tube to swing down.

The illustrations Figs. 18-6 and 18-7 show examples of the use of expulsion type fuse-switches.

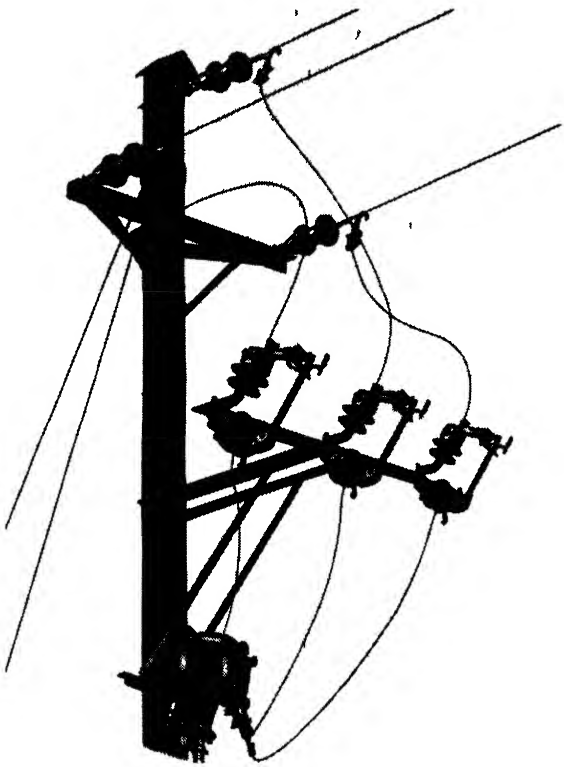
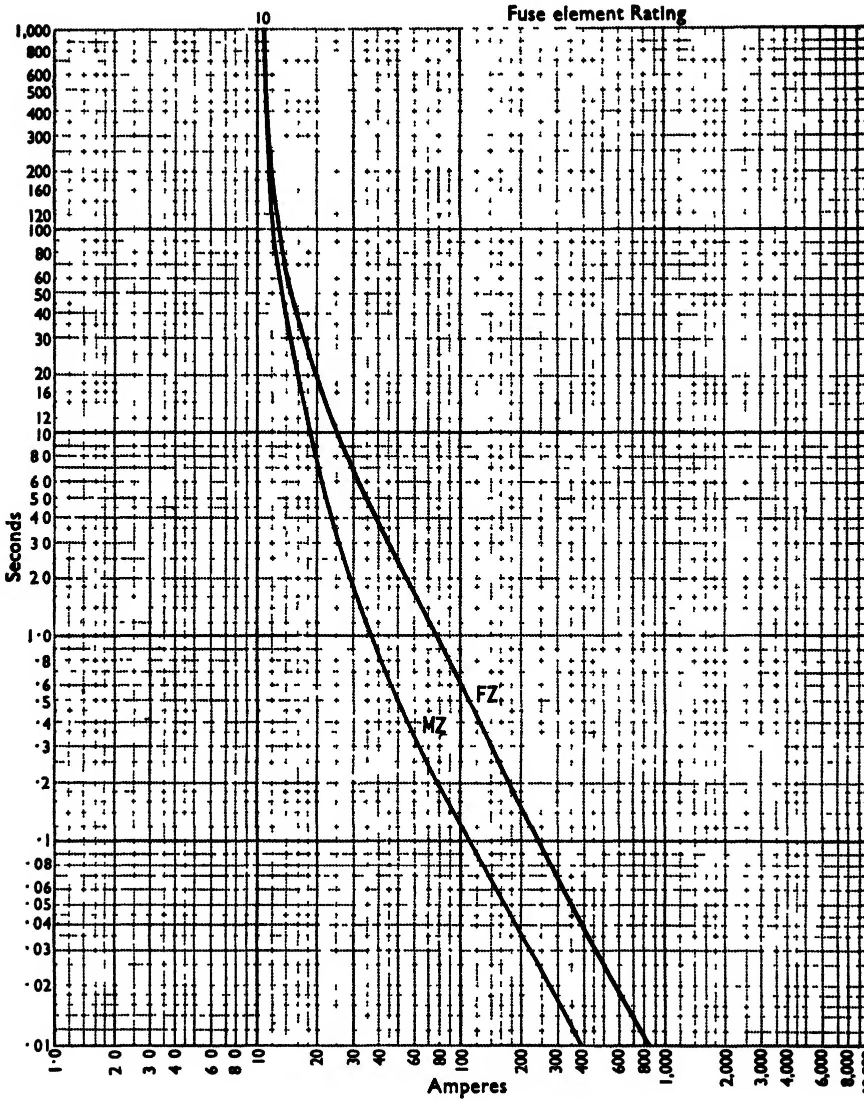


FIG. 18-7.—*Expulsion type fuses at junction of overhead line and cable feeder (Johnson & Phillips Ltd.).*

The fuse elements used in this design are made for fast or slow operating times, typical differences being shown in Fig. 18-8 where the pre-arcing (melting) times are plotted against current for a 10 ampere element.



MZ=STANDARD FZ=FAST-ACTING

FIG. 18-8.—*Curves showing speed difference between two types of element—10 ampere rating shown (Johnson & Phillips Ltd.).*

In Chapter XII we have noted some of the problems associated with discrimination between medium voltage fuses in series. Similar problems arise at higher voltages and concern the condition where fuses have to discriminate with other fuses in series and also where fuses must discriminate with other apparatus fitted with overcurrent devices, e.g. a circuit-breaker. In the first case, the problem has two aspects (a) where the fuses in series are all of a like type and make and (b) where they may be of different types, e.g. cartridge and expulsion, which exhibit entirely different time/current characteristics. In this latter case, and in that where fuses are required to discriminate with a circuit-breaker, a knowledge of the time/current characteristics is an essential requirement for predicting the possibilities of discrimination.

Where fuses of a like type are used, it is possible to determine with reasonable accuracy the range of discrimination as between the various normal current ratings and it is of interest to note that, based on a series of power tests on Johnson & Phillips Type "D" fuses (Fig. 18-2), discrimination will occur between fuse and fuse provided they bear a ratio of 0·75 or less to each other. Thus if in Fig. 18-9, fuse A is rated 75 amperes, then to ensure discrimination, fuse B must have a standard normal current rating nearest *below* the value 75.0·75, i.e. 56·25 amperes, showing that a 50 ampere fuse will discriminate with a 75 ampere fuse but that one of 60 ampere rating will not.

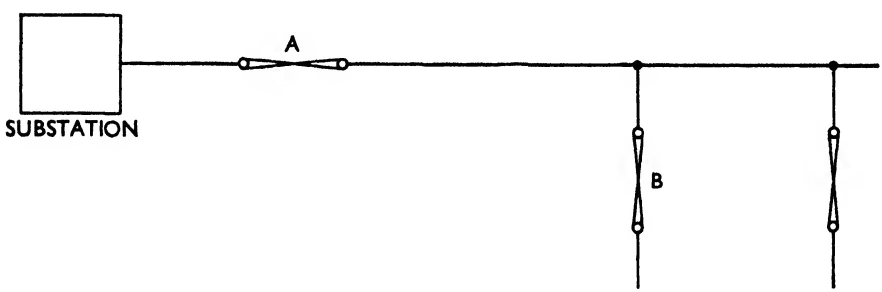


FIG. 18-9.—*Illustrating fuses in series.*

This may be illustrated in another way as shown in Fig. 18-10. In this the characteristic time/current curves for three ratings of expulsion fuse are shown by the lines A-A. The lines B-B have then been drawn to represent 75 per cent of the values given by A-A, and it is now possible to state that the time/current curve for any other fuse rating, intermediate to those shown, must not fall in the shaded area of the nearest higher fuse rating. For example, Fig. 18-11 shows how the time/current curve for a 50 ampere fuse lies within the shaded area for a 60 ampere fuse and thus there will be no discrimination. Similarly, if the curves for 30 ampere and 40 ampere fuses are plotted, it would be found that the 30 ampere curve would be clear of the shaded area associated with a 50 ampere fuse and would therefore

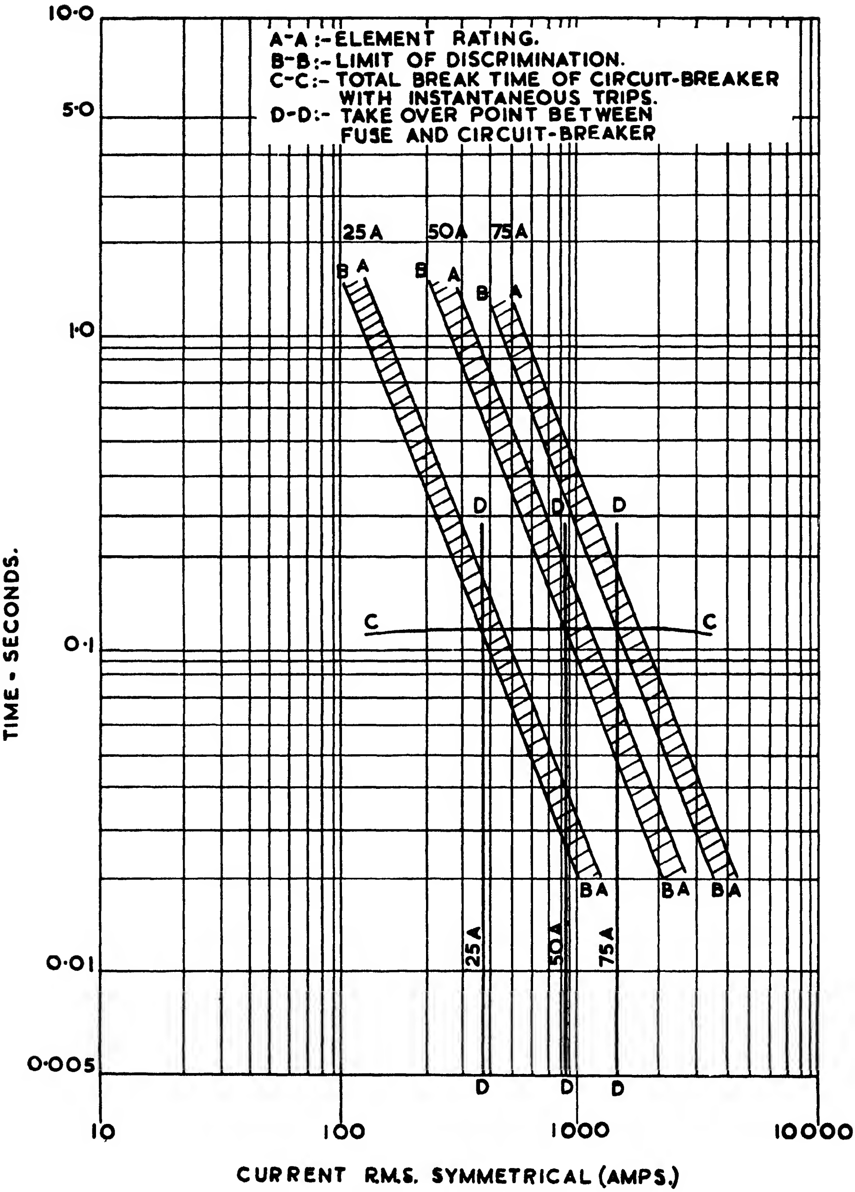


FIG. 18-10.—*Time/current characteristics for expulsion fuses and circuit-breaker with instantaneous trips to demonstrate discrimination (Johnson & Phillips Ltd.).*

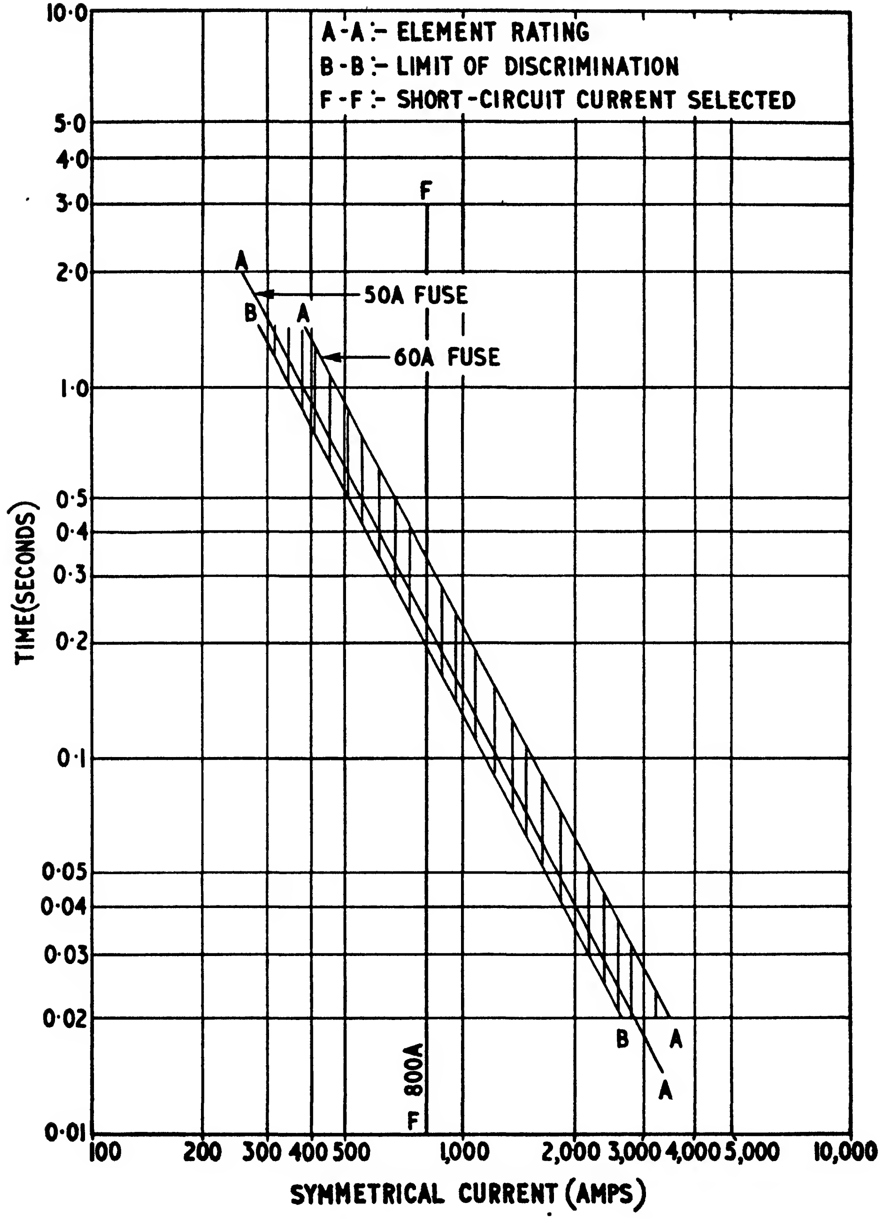


FIG. 18-11.—*Time/current curves for 50 and 60 ampere elements showing inability to discriminate (Johnson & Phillips Ltd.).*

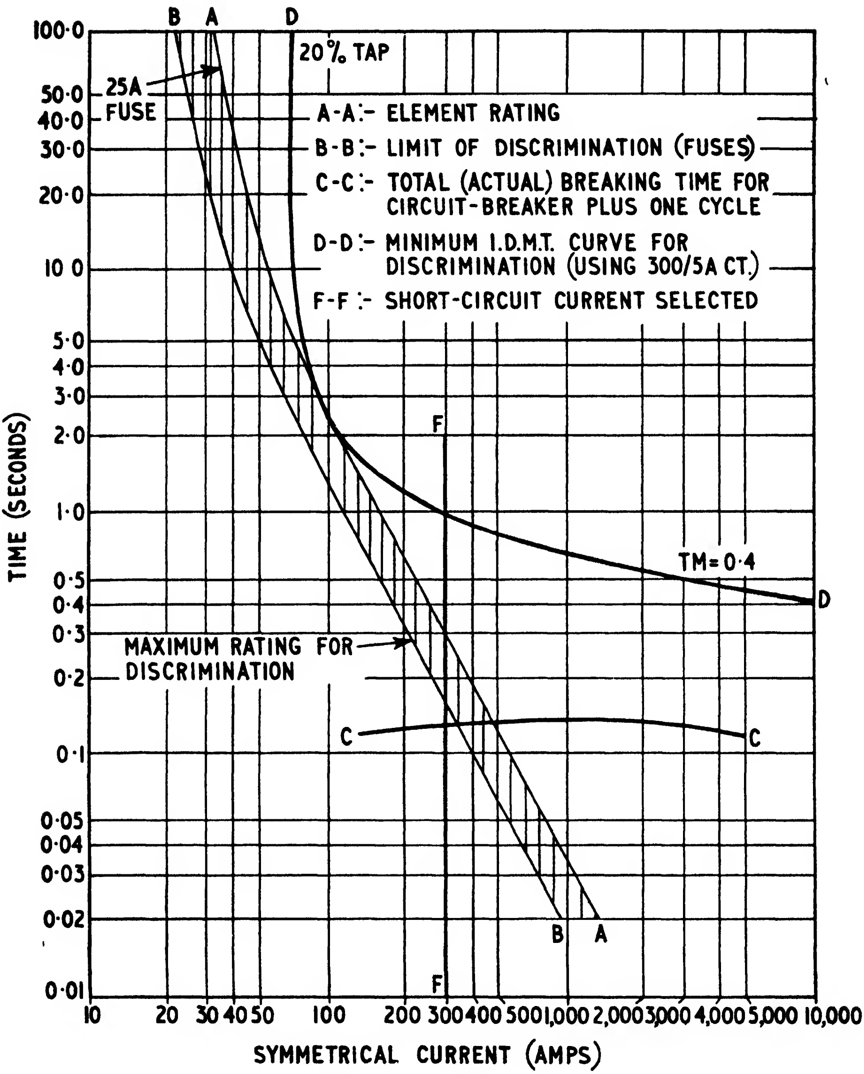


FIG. 18-12.—*Discrimination between a circuit-breaker and 25 ampere fuse (Johnson & Phillips Ltd.).*

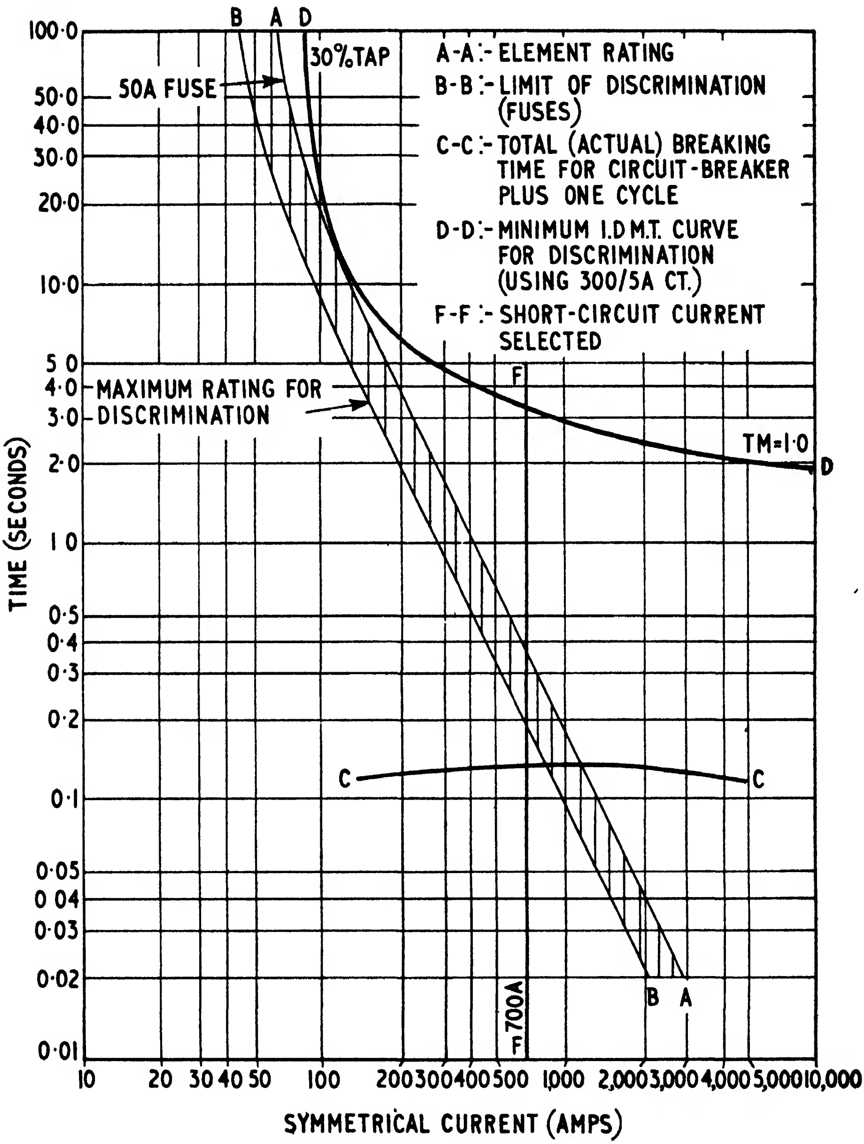


FIG. 18-13.—*Discrimination between a circuit-breaker and 50 ampere fuse (Johnson & Phillips Ltd.).*

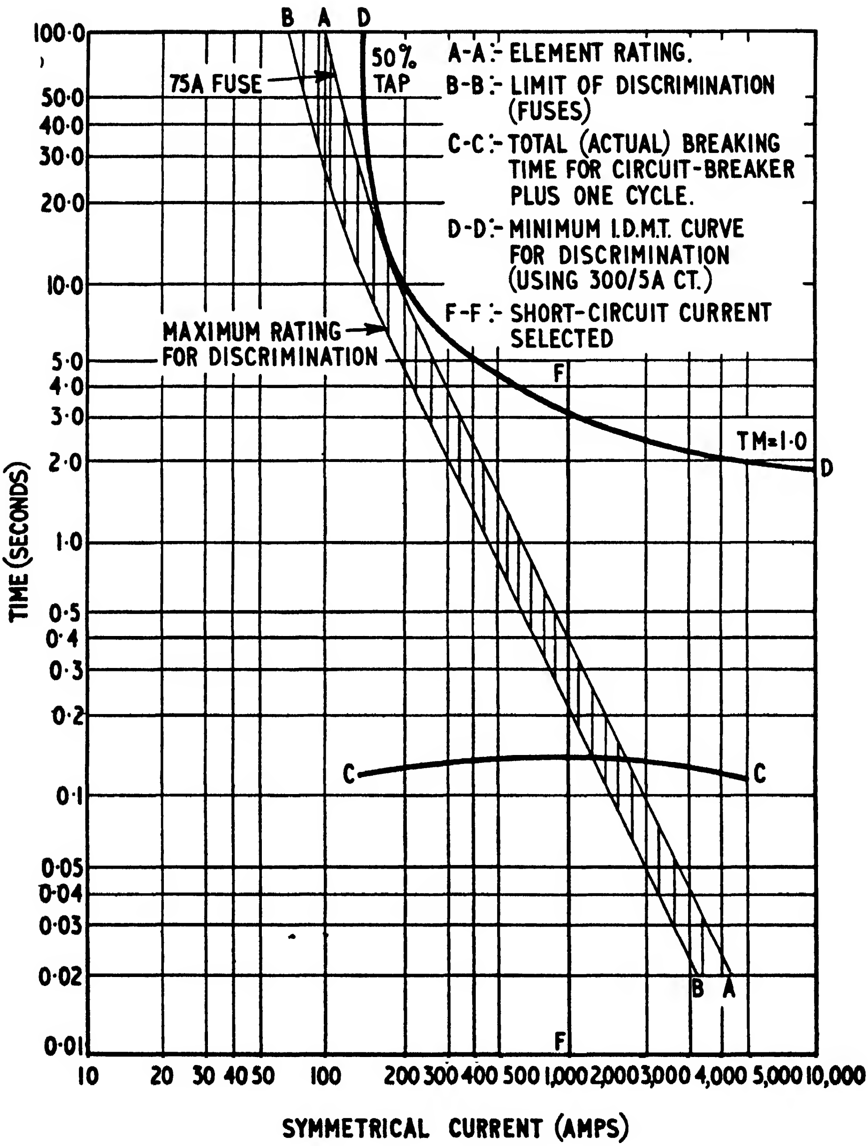


FIG. 18-14.—*Discrimination between a circuit-breaker and 75 ampere fuse (Johnson & Phillips Ltd.).*

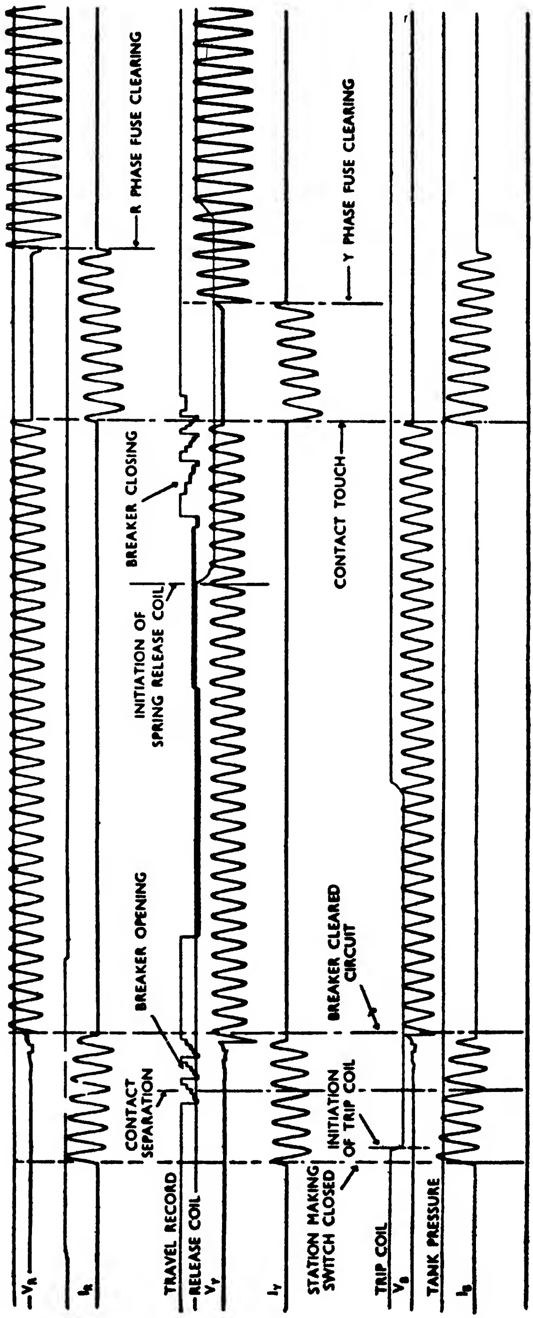


FIG. 18-15.—*Oscillographic record of test to satisfy curves of Fig.* 18-13 (*Johnson & Phillips Ltd.*).

discriminate but the curve for a 40 ampere fuse would encroach on this shaded area and would not therefore discriminate. Fig. 18-10 has been extended to show the total break time of a circuit-breaker with instantaneous trips over the range of currents applicable to the fuses, and represented by curve C-C. Where this curve crosses the lines B-B is the "take-over" point for each size of fuse and from these points, vertical lines D-D have been projected to the current scale. Thus for any fault current *less* than that represented by a line D-D the fuse will not operate, the circuit-breaker clearing the fault. Any current in *excess* of the values represented by D-D will cause operation of both breaker and fuse, assuming in both cases that the protective devices on the circuit-breaker are set for instantaneous trip. Thus, with transient faults of low magnitude, the circuit-breaker will clear without any fuse operating and to provide for rapid restoration of supply, the circuit-breaker will be provided with means to automatically reclose it within say 20/25 cycles. To enable this to be achieved, rapid resetting of the closing mechanism is essential and in the design under discussion (Johnson & Phillips Ltd.), resetting is obtained before the moving contacts have settled in the buffer dashpots at the end of the stroke. If, on reclosure, the fault has not cleared, then the circuit-breaker will reopen and lock-out.

It is of interest here to note briefly some details of tests made to determine the relation between a circuit-breaker and fuses, the former being a 3-pole unit of the type shown in Chapter VI, Fig. 6-2, arranged for high-speed auto-reclosure, the fuses being of the type shown in Fig. 18-2. The test circuit was three phase but the fuses were fitted in two phases only with a solid link in the third.

The tests were based on the condition that the circuit-breaker, having interrupted the fault, should reclose and, if the fault persisted, hold in until the fuse cleared the circuit. The high-speed open/close operation allowed for a dead time of approximately 25 cycles and an inverse definite minimum

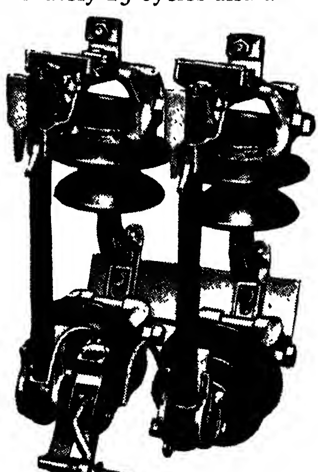


FIG. 18-16.—*Repeater switch arrangement for automatic circuit restoration, using two expulsion type fuse-switches per phase. Shown in original state, both fuse-elements sound (Johnson & Phillips Ltd.).*

time relay ensured that the breaker remained closed for a sufficient time to allow the fuses to operate and finally clear the circuit.

Based on what has been noted in relation to Fig. 18-10, three sets of curves are produced in Figs. 18-12, 18-13 and 18-14, for 25, 50 and 75 ampere fuses respectively. On each of these the characteristic curve representing one setting of an I.D.M.T. relay has been superimposed (curve D-D), and the tests undertaken had the purpose of proving that the operating times for both the circuit-breaker and the fuses, accorded with these curves, and showing that the conditions noted earlier would be fully satisfied.

As the fuse rating was increased, so the fault current was raised, the latter values being 300, 700 and 1 000 amperes respectively, as shown on the curves by the line F-F.

Fig. 18-15 shows the oscillographic record of a test related to the curves in Fig. 18-13, the fuses being in phases R and Y with the solid link in phase B.

In the preamble to this chapter, we noted the attention presently being given to automatic reclosure to restore the supply after disconnection due

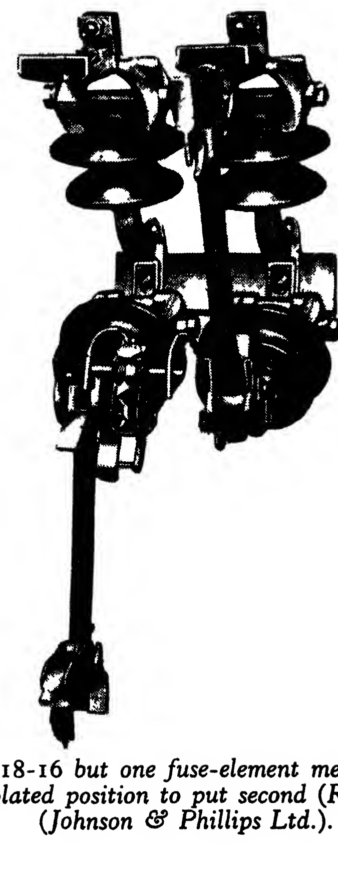


FIG. 18-17.—*As Fig. 18-16 but one fuse-element melted and fuse-switch has swung down to isolated position to put second (R.H.) fuse in circuit (Johnson & Phillips Ltd.).*

to a fault of a transient nature. Such an arrangement is made possible by using two or more expulsion fuse-switches of the type described per phase. In this arrangement, the service fuse operates and swings down to its isolated position and in so doing it automatically switches a second fuse into circuit so that if the original fault has disappeared, service to the consumer is restored at once, the outage time being of the order of 0·4 second. The arrangement is shown in Figs. 18-16 and 18-17.

From Fig. 18-16 it will be seen that at the lower end of the left-hand fuse-switch, there is a contact bar carried on the end of an operating arm and held open against a compression spring by means of a catch. The left-hand fuse, in swinging down, strikes this catch, releasing the operating arm which moves to restore the circuit when it bridges the two fixed horn contacts between the fuses. The principle of the arrangement is shown diagrammatically in Fig. 18-18, the contacts shown open between the two fuses closing when the left-hand fuse operates.

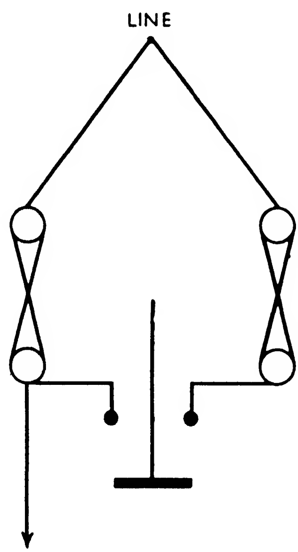


FIG. 18-18.—*Diagrammatic arrangement of repeater switch connections (Johnson & Phillips Ltd.).*

The arrangement as shown allows for one repeat only but two or even three can be covered by using three or four fuse-switches per phase with a repeater between each. Fuse element renewal is carried out in a manner similar to that described earlier and the rewired tube is closed to restore combination after opening the repeater switch.

An oscillographic record of a short-circuit test on a repeater combination as described is shown in Fig. 18-19, the test in this case being single phase.

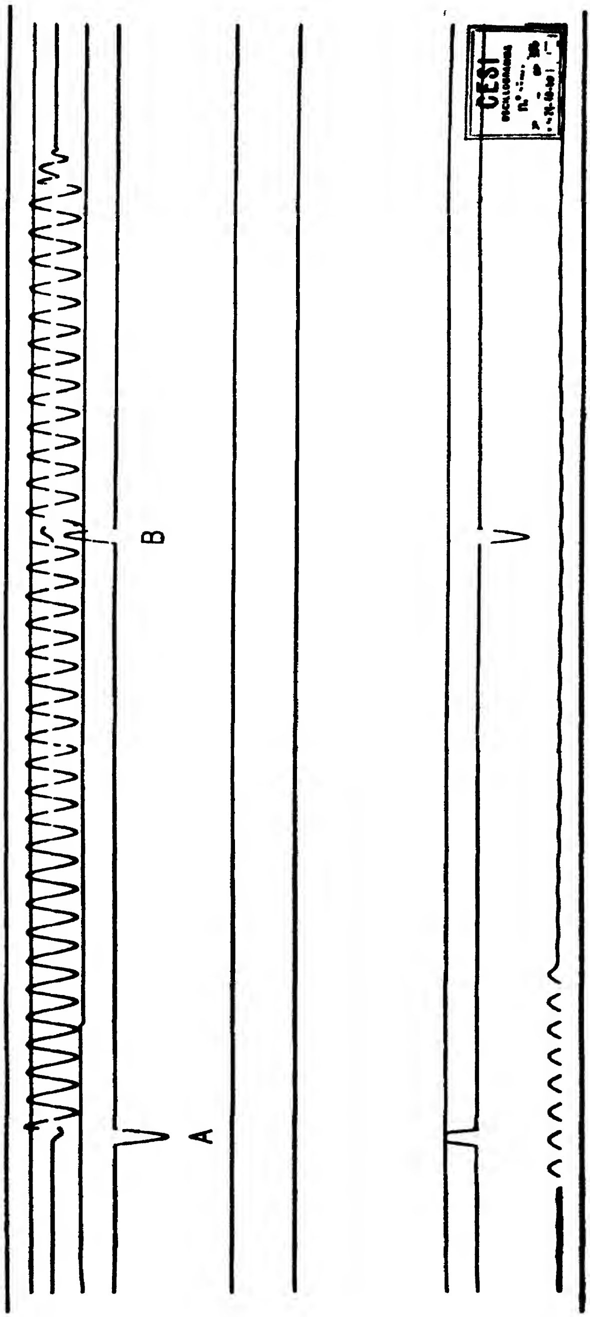


FIG. 18-19.—*Oscillogram of test on an expulsion fuse repeater unit in a single phase circuit at a prospective current of 7·9 kA equivalent to 150 MVA at 11 kV* (Johnson & Phillips Ltd.).

In this oscillogram, the first fuse is noted as clearing at "A", followed by a time delay of approximately 0·4 seconds while the repeater switch operates to bring the second fuse into circuit and to clear the still existing short-circuit at "B".

For locations where the fault value can exceed 150 MVA and/or for higher voltages, the current-limiting cartridge fuse may be employed. The current-limiting ("cut-off") feature of h.r.c. fuses has already been noted in our discussion on those for medium voltage (Chapter XII) and similar valuable characteristics are obtained in those for use on higher voltages. Furthermore, a striker pin arrangement as previously discussed can be provided and where this is employed, it may be used to release a latching mechanism so that after operation of the fuse, the fuse-link swings down to an isolated position exactly as noted in Figs. 18-2 and 18-3 for expulsion

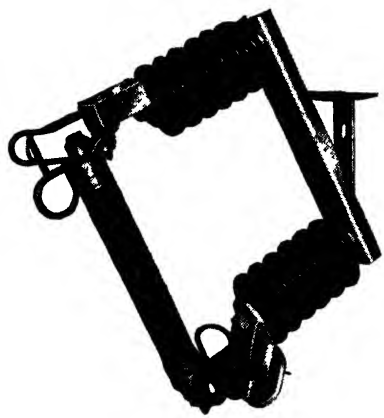


FIG. 18-20.—*High-voltage fuse-switch employing cartridge type fuse-link with striker-pin (EMP Electric Ltd.).*

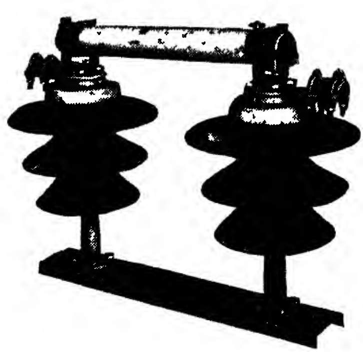


FIG. 18-21.—*Non-disconnecting type current-limiting cartridge fuse for horizontal mounting (EMP Electric Ltd.).*

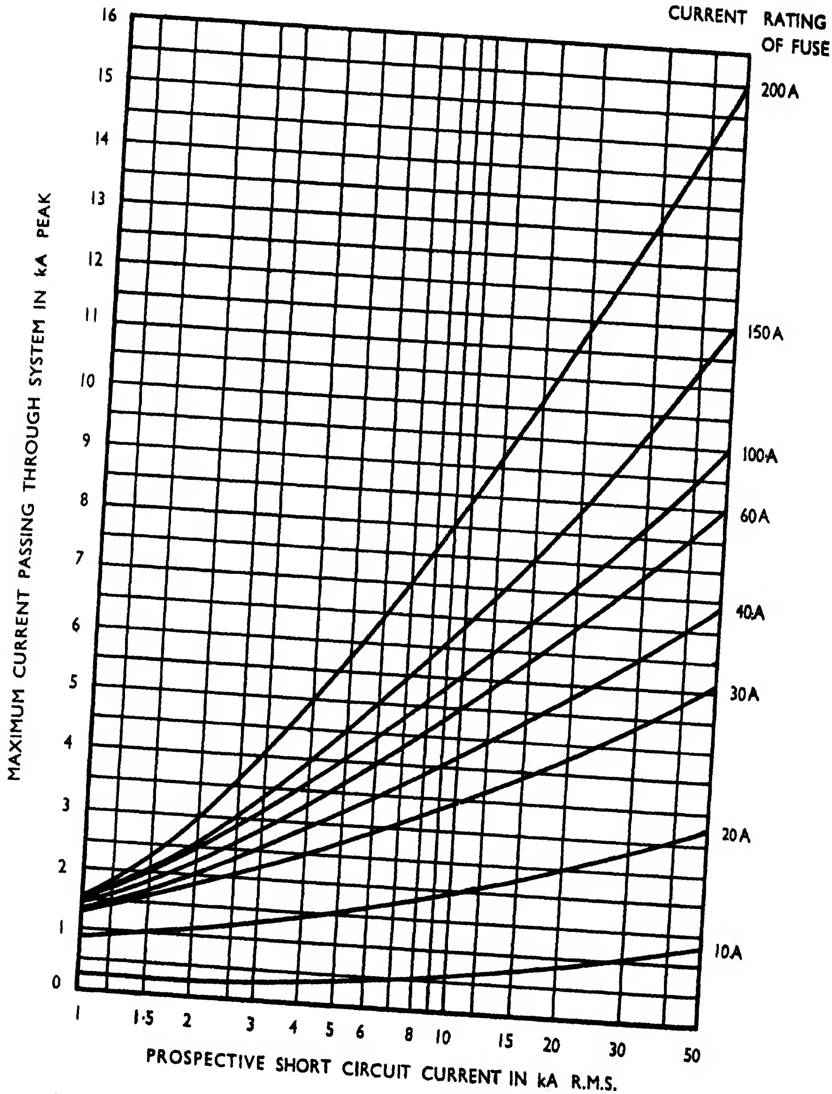


FIG. 18-22.—"*Cut-off*" *characteristic of high-voltage h.r.c. fuses (EMP Electric Ltd.).*

types. A fuse-switch incorporating a powder-filled cartridge fuse is shown in Fig. 18-20, the outer barrel being made of glass fibre to withstand rough handling.

Many outdoor applications arise where the swing down isolating feature is not essential and in such cases, a non-disconnecting type as shown in Fig. 18-21 can be employed and, if required, mounted horizontally instead of vertically as is essential in the isolating type.

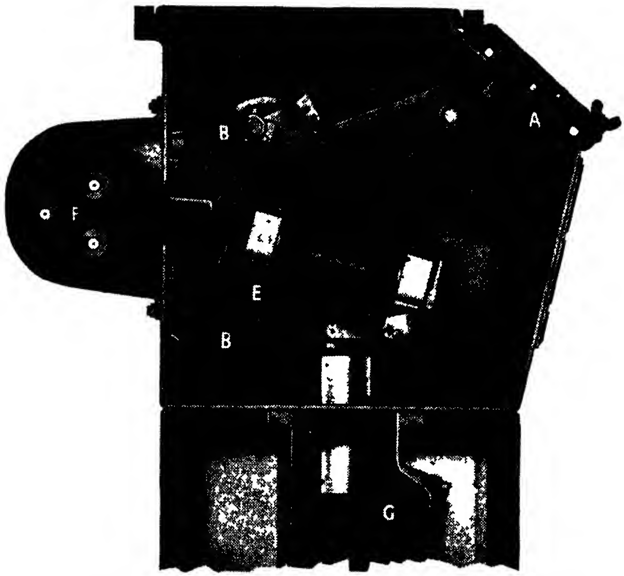
The "cut-off" characteristics of these cartridge-type fuses are shown in the curves, Fig. 18-22, it being noted that at the lower values of fault current the "cut-off" effect is based on a test circuit in which the maximum short-circuit could reach 50 kA r.m.s., thereby presupposing a lower rate of rise of fault current.

In this current-limiting design, the voltage range is from 2·4 kV up to and including 132 kV with interrupting capacities (three phase) of 150 to 1 500 MVA. Time/current characteristics may be of the fast or slow-acting type as may be required by the application.

In considering the various types of high-voltage switchgear units available for indoor use (Chapter X) we noted the combination of fuses and load-breaking switches contained within a common housing. Such units are also available for outdoor use, one design being shown in Fig. 18-23.

FIG. 18-23.—*Outdoor metal-enclosed fuse-switch unit up to 11 kV (A. Reyrolle & Co. Ltd.).*

In this the fuse-links engage with fixed contacts of the high-pressure butt type and have tripping devices such that when any one fuse-link operates, the latching-in mechanism is upset so that all three fuse-links move to the "Off" position and the fuse-switch cannot be reclosed until a new fuse-link has been fitted. The constructional features of this unit are shown in Fig. 18-24 which shows the fuse-switch in the closed position. This



A. ACCESS COVER FOR FUSE REPLACEMENT.
B. EARTH SHIELD.
C. INSULATING-BARRIER.
D. FUSE-LINK.
E. FUSE-SWITCH BUTT TYPE CONTACTS.
F. BUSBAR CHAMBER
G. OUTGOING CABLE BOX.

FIG. 18-24.—*Cross-section through fuse-switch unit with fuse-switch closed (A. Reyrolle & Co. Ltd.).*

illustration also shows how, for extensible units, busbars may be mounted at the rear of the unit, the bars being of copper rod embedded in cast resin insulation.

Fuse replacement is made through the access cover, the raising of which moves the fuse-links from the "off" to an "isolated" position, i.e. they are now disconnected on both sides. In this isolated position the links are brought opposite the aperture, as shown in Fig. 18-25 and at the same time, an earth shield, also seen, is automatically placed over the fixed (live) contacts on the incoming or busbar side.

A cable earthing switch and test plugs for cable testing can be provided on this unit, the latter being capable of insertion only after the cable has been earthed. Having inserted the plugs, the cable earth can be removed to permit the test on the cable to be carried out, but before the plugs can be removed, the cable earthing switch must again be closed.

As with indoor types, the fuse-switch can be applied as a tee-off unit in conjunction with a ring main switch, the diagram for such arrangement being that shown in Fig. 18-26.

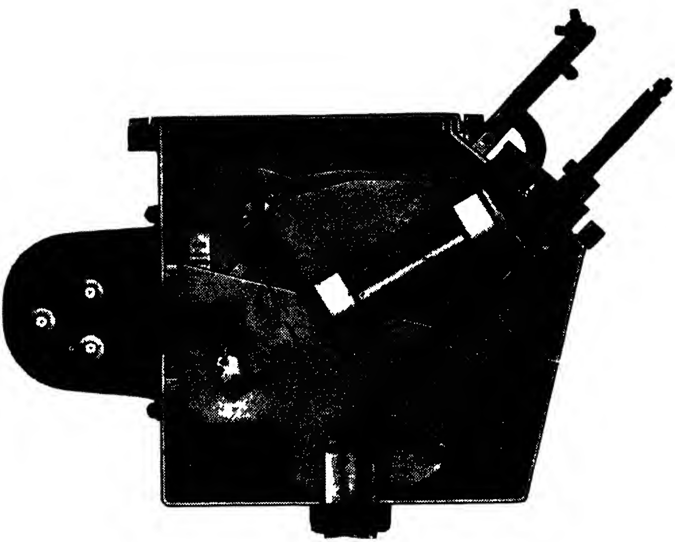
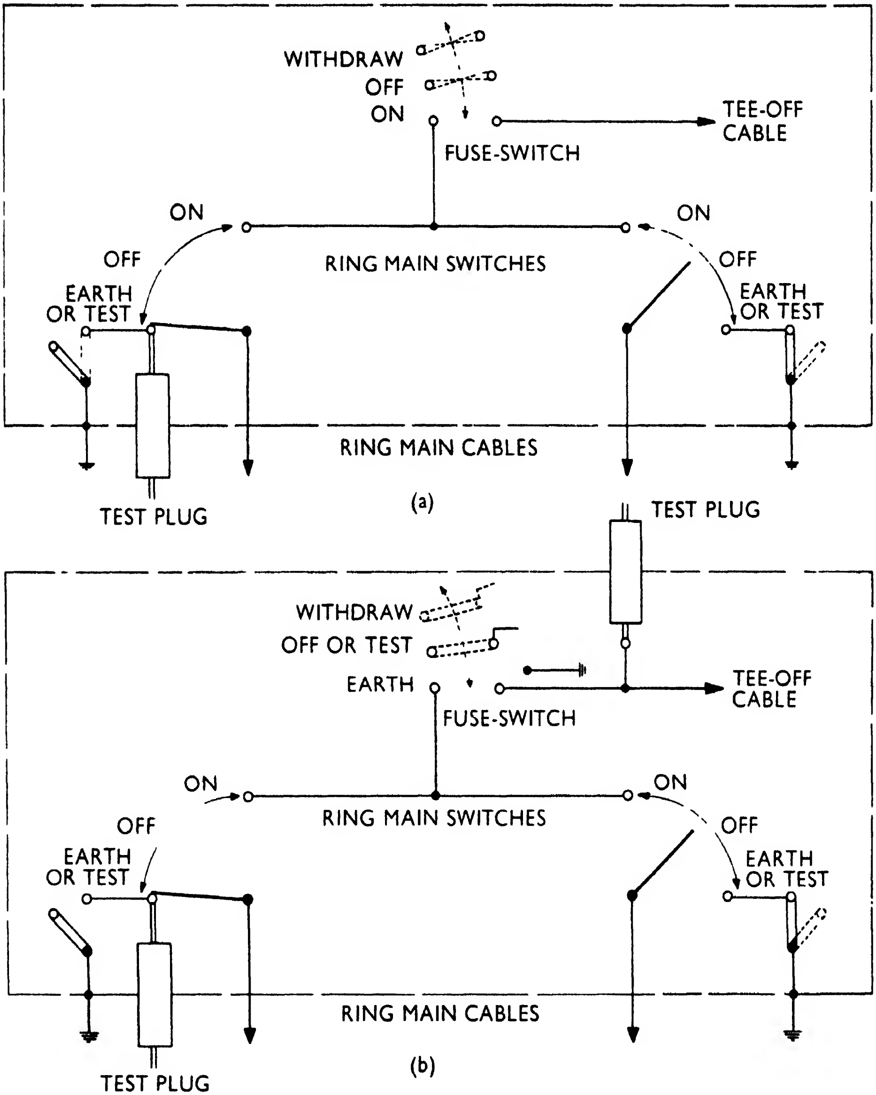


FIG. 18-25.—*Fuse-switch in "isolated" position with earth shield over fixed (live) contacts. Also shows cable test plugs inserted* (*A. Reyrolle & Co. Ltd.*).

Note that in this design of fuse-switch unit, the fuse-links are normally mmersed in oil and therefore must be oil-tight, but the oil plays no part in the process of arc extinction. The oil acts to assist the function of the switch when used for normal load-breaking. Although described here as an outdoor unit, it can equally well be employed for indoor installations.

AUTOMATIC RECLOSERS FOR RURAL DISTRIBUTION

Rural distribution is, in the main, at 11 kV and by means of overhead lines. With the relatively close conductor spacing at this voltage, such lines are prone to interruption due to straw or small branches of trees being blown across them, or by the wing span of birds. As with other overhead lines, they are subject to lightning disturbances and all of these things result in what is known as transient failure, i.e. it is only very temporary and the cause is quickly eliminated.



(A) ARRANGEMENT WITH PROVISION FOR EARTHING & TESTING RING MAIN CABLES ONLY.
(B) ARRANGEMENT WITH ADDITIONAL FACILITIES FOR EARTHING & TESTING TEE-OFF CABLE: IN THIS, THE FUSE-LINKS ARE REPLACED WITH SPECIAL ASSEMBLIES IN WHICH THE END CAPS ARE INSULATED FROM EACH OTHER AND THE CABLE SIDE END CAP HAS AN EXTENDED CONTACT TO ENGAGE WITH THE EARTH CONTACT WHEN THE ASSEMBLY IS IN THE "ON" POSITION.

FIG. 18-26.—*Diagrammatic arrangements of ring main switch unit with tee-off fuse-switch (A. Reyrolle & Co. Ltd.).*

If, as is common in rural distribution, circuits connected to the network are protected by fuses of the types described at the beginning of this chapter, all such incidents could cause fuse operation and the supply to a consumer may thus be interrupted for some lengthy period of time while fuse replacement is achieved, the time depending on the availability of a service engineer, locating the fuse which has operated and how far he has to travel to the point of fault.

The problem then is to find some means whereby a circuit may be automatically restored after a short time delay so that if the fault is of a transient nature and is self-clearing, supply is only interrupted temporarily.

We have seen, on page 618, how this objective has been achieved by the use of repeater fuses and on pages 171 and 174 how a pole mounting oil circuit-breaker can be arranged to give a number of reclosures by means of a falling weight mechanism.

Here we shall be concerned to note the availability of specially designed automatic circuit reclosers which have been developed to operate in conjunction with fuses having suitable time/current characteristics or with, in at least one case, an automatic sectionaliser. It is important here to place emphasis on the fuse characteristics, the reason for which will become clear as we proceed.

Fig. 18-27 may be regarded as being typical of recloser application, the recloser being inserted in the main overhead line with slow-acting fuses to protect the subsidiary consumer circuits.

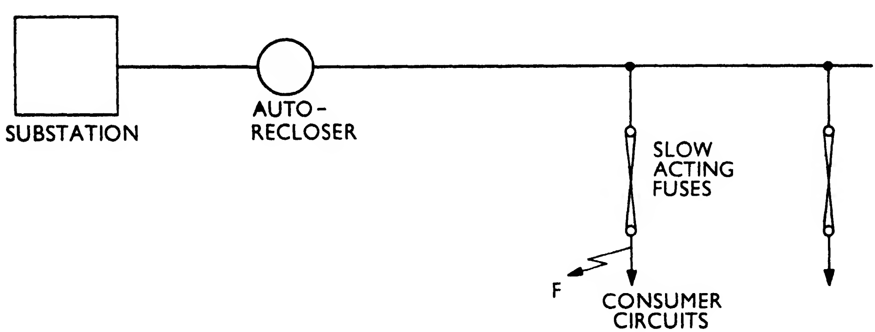


FIG. 18-27.—*Application of automatic recloser and fuses.*

The recloser will be fitted with a sequence timing mechanism to provide, for example, an operating sequence of two instantaneous trips to be followed by two time-delayed trips and then lock-out.

Thus, if a fault occurs at point F as shown, the recloser will open to interrupt the short circuit before the fuse-link can operate and the recloser remains open for approximately one second. During this time the fault path de-ionises and experience shows that in the majority of cases the cause of the fault will have disappeared. After the one-second period the recloser will automatically reclose and if the fault has disappeared, supply is restored

but if it has not, the recloser will open again instantaneously and remains open for one second before reclosing. If the fault still persists it may now be presumed to be permanent and the next trip is purposely delayed to permit the fuse-link to operate and isolate the fault. The recloser now closes to restore supply to remaining (healthy) circuits leaving only the faulty circuit isolated.

If the fault current is insufficient to cause the fuse-link to operate during this first delayed tripping operation, the equipment recloses and is followed by a second delayed tripping operation to give the fuse-link a second chance to clear the fault. Should the fault persist, the recloser will lock-out and the operating mechanism must then be reset manually.

This sequence is best illustrated by the operating cycle diagram given in

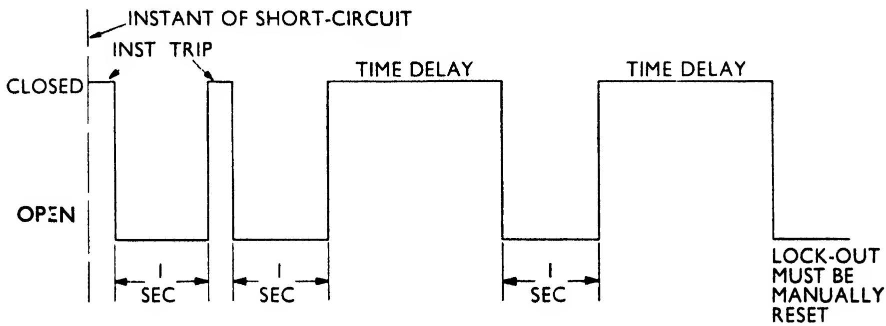


FIG. 18-28.—*Operating cycle for auto-recloser.*

Fig. 18-28 but it may be noted that the sequence can be varied to suit operational requirements, e.g. the total of four tripping operations can be in any combination of instantaneous or delayed such as one instantaneous and three delayed or three instantaneous and one delayed.

If the fault is cleared at any time during a sequence *before* lock-out, the mechanism of the recloser will reset so that it will be ready to commence the entire sequence again on the occurrence of any further fault.

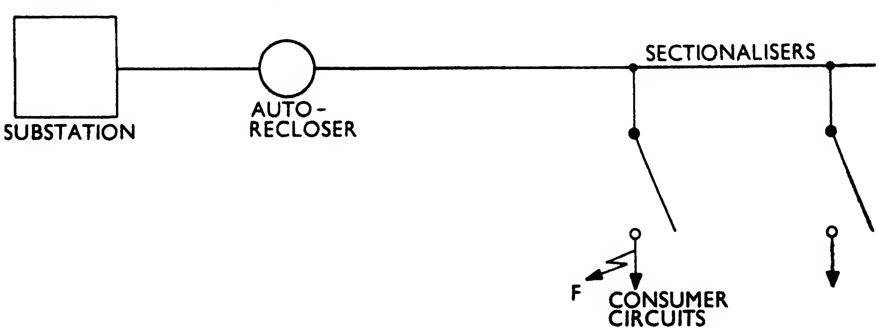


FIG. 18-29.—*Application of auto-recloser and sectionalisers.*

The satisfactory operation of a recloser in association with fuses depends on the degree of co-ordination obtained, requiring that the time/current characteristic of the recloser be graded with that of the fuse to give optimum discrimination. Thus the selection to give this must ensure.

(a) That the recloser will perform the first two operations without causing the fuse-link to deteriorate, and

(b) That the opening of the recloser will be sufficiently delayed on the third and fourth operations to permit the fuse-link to operate.

Circumstances will arise where adequate discrimination as described cannot be obtained or alternatively the use of fuses may be considered undesirable. In these cases, the fuses in the spur lines may be eliminated by the use of automatic sectionalisers which are in effect oil switches designed to isolate a faulty circuit after a pre-selected number of opening and closing operations of the protecting recloser and during the "dead" time of the latter. Thus the recloser acts as before to restore supply to healthy sections of a system after the faulty section has been isolated. In this arrangement, it is usual to arrange that the recloser is set for instantaneous tripping operations only.

Figs. 18-29 and 18-30 represent the conditions for this arrangement from which it will be seen that if after the three instantaneous trips on the recloser the fault has not cleared itself, the sectionaliser on the faulty line

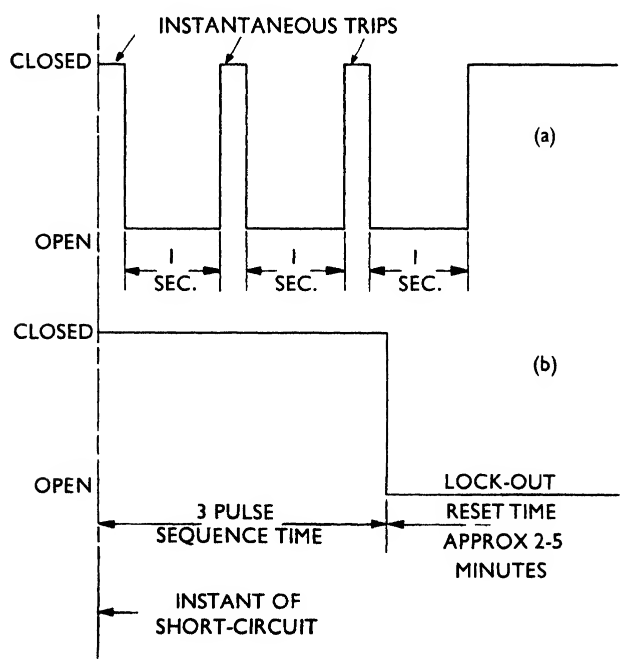


FIG. 18-30.—*Operating cycles for auto-recloser (a), and sectionaliser (b).*

will time itself out to open and clear the fault but breaking no current as the recloser is at that instant open.

This description of the application of reclosers in association with fuses or sectionalisers is of necessity brief. There are, in practice, many other problems which require more detailed study, as for example where circumstances require reclosers in series, where fuses of various ratings are employed in spur feeders beyond the recloser and possibly when, on a spur feeder, there may be fuses in series. These and other aspects related to recloser application are noted in the papers listed in the bibliography and, on page 609 we have noted some data concerning the possibilities of discrimination between one make of fuses in series.

It may be noted here that the breaking capacity of reclosers is relatively low, i.e. not exceeding 75 MVA at 11 kV and it follows that if the short-circuit level at the main substation is say 150 or even 250 MVA, the nearest recloser must of necessity be installed some distance from that point (probably several miles) so that the fault level has been reduced (due to line impedance) to 75 MVA or less.

Finally a brief look at typical designs of recloser and sectionaliser. In that shown in Fig. 18-31 each recloser is a single pole single break device, three units being coupled by a torque rod to form a three phase assembly.

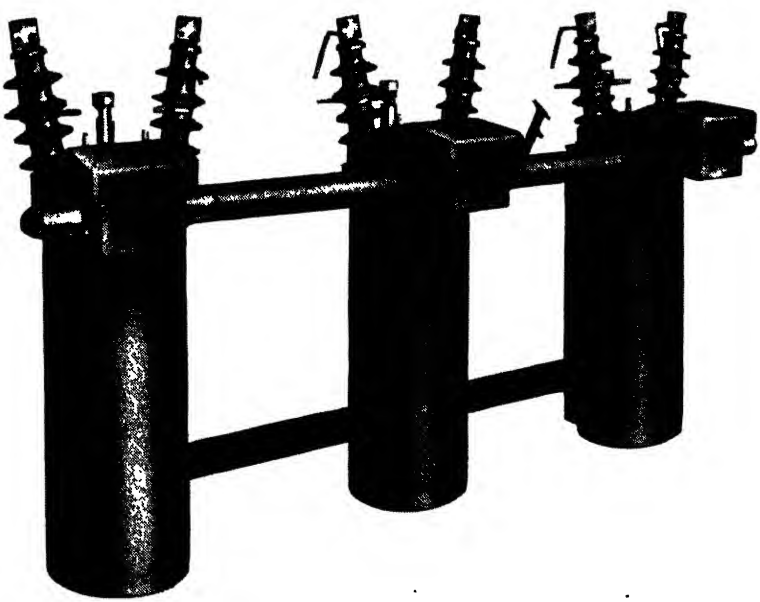


FIG. 18-31.—*Three pole automatic circuit recloser (Associated Electrical Industries Ltd.).*

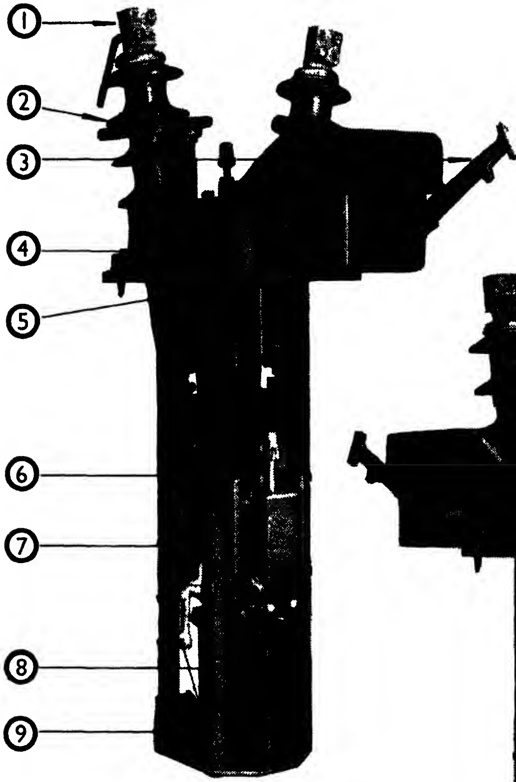


FIG. 18-32.—
Front view of automatic recloser removed from its tank (Associated Electrical Industries Ltd.).

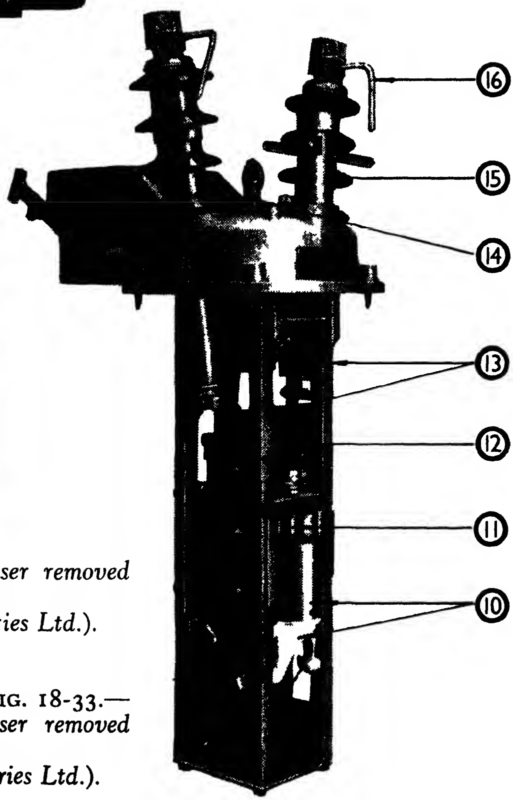


FIG. 18-33.—
Rear view of automatic recloser removed from its tank (Associated Electrical Industries Ltd.).

1. CLAMP TYPE TERMINAL CONNECTORS
2. SINGLE PIECE PORCELAIN BUSHING INSULATORS
3. EXTERNAL OPERATING LEVER
4. CAST TOP PLATE
5. OPERATION COUNTER VISIBLE UNDER MECHANISM HOOD
6. MONITOR
7. TIMING DASHPOT
8 MAIN OPERATING SOLENOID
9. NON-LINEAR RESISTOR SHUNTING THE OPERATING COIL
10. ARC-CONTROL DEVICE AND FIXED CONTACT HOUSING
11. MOVING CONTACT ROD
12 INSULATION OPERATING ROD
13 INSULATION SUPPORTS
14. REMOVABLE LIFTING EYE
15. MECHANICALLY-OPERATED WEATHERPROOF ON/OFF INDICATOR
16. ARCING HORN

This design is available in two forms, one to provide a cycle of two instantaneous openings followed by two time delayed openings before locking out and another to provide a cycle of up to four instantaneous openings before locking out. The first of these is intended for use on lines incorporating remote slow-acting fuses and the second for use on lines which are solidly connected without remote fuses.

The main design features are noted in Figs. 18-32 and 18-33. The opening operation is caused automatically by the passage of the fault current through a series operating coil which pulls down a solenoid plunger to open the contacts and interrupt the fault current. The plunger then returns to its original position under spring action and the contacts reclose. The mechanism provides for quick-make and quick-break action of the contacts. An oil-filled dashpot connected to the mechanism controls the open times on

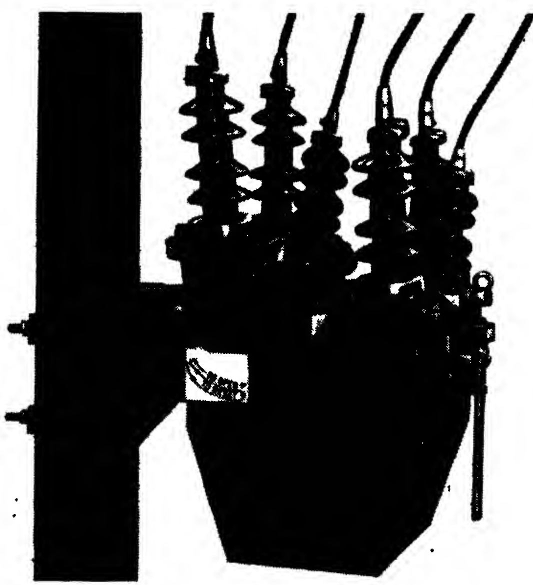


FIG. 18-34.—*Three phase automatic circuit recloser (A. Reyrolle & Co. Ltd.).*

the unit and also controls the time-delayed openings in one form of the design. A monitoring device, comprising a toothed rack, (seen at 6 in Fig. 18-32) is lifted in steps by a catch during each closing stroke of the solenoid plunger and a timing device is incorporated to regulate the speed at which it can be reset. This toothed rack also provides the lock-out feature in that when the last tooth has been picked up, a lock-out link is positioned so that should the unit open again the lock-out mechanism operates to prevent further reclosure. Additionally it is arranged to control the open or closed positions of the main valve in the timing dashpot, this valve being held open for the first two operations to give instantaneous

opening and then closed to ensure two time-delayed openings. This function is automatically performed as the second tooth on the rack is lifted.

The lever 3 in Fig. 18-32 provides means whereby the recloser can be closed or opened manually by means of a pole from ground level. The mechanism is so arranged that no reclosing operations are immediately available when a unit is closed manually, so that should it be closed on to a fault it will open automatically and lock-out.

The design of automatic recloser shown in Fig. 18-34 is one having all three phases in a common tank. Its constructional features are shown in more detail in Fig. 18-35.

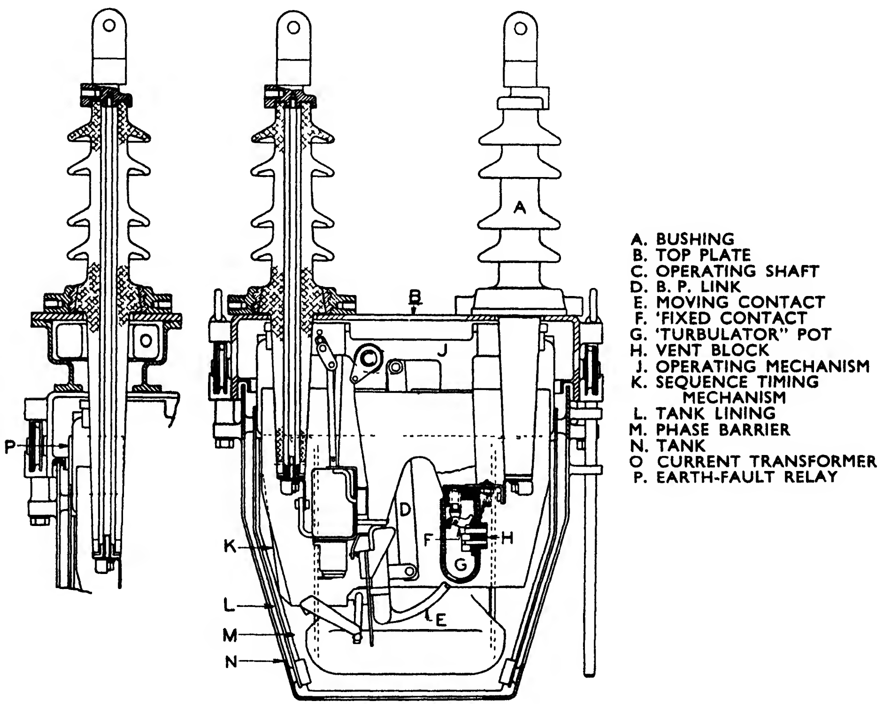


FIG. 18-35.—*Sectional view of recloser interior* (*A. Reyrolle & Co. Ltd.*).

The unit in this design is closed by means of an electromagnetically charged spring mechanism and is held by a roller toggle against the action of a kick-off spring. Passage of fault current through self-resetting series overcurrent coils causes the recloser to open whereupon the sequence of reclosing and opening operations as described earlier (as in Figs. 18-28 and 18-30) proceed automatically, locking-out should the full sequence be completed.

The energy for closing is derived from what is described as a multi-stroke electromagnet, the coil of which is connected across two lines of the incoming supply through a pair of auxiliary contacts as shown in Fig. 18-36.

These contacts close as the recloser contacts open, thus energising the magnet, the armature of which moves downwards to start the charging process of the closing spring via a clutch mechanism. When the armature is almost fully home, the auxiliary contacts separate, de-energising the magnet

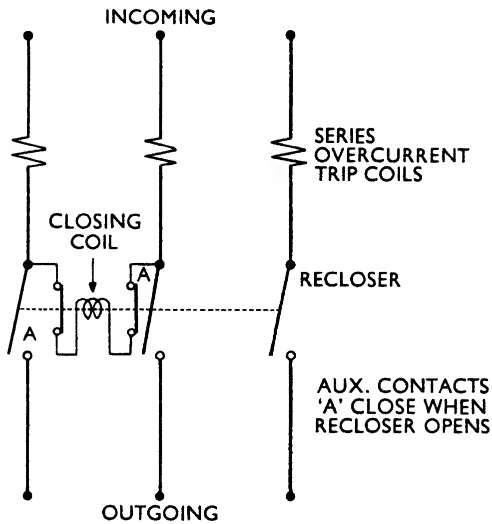
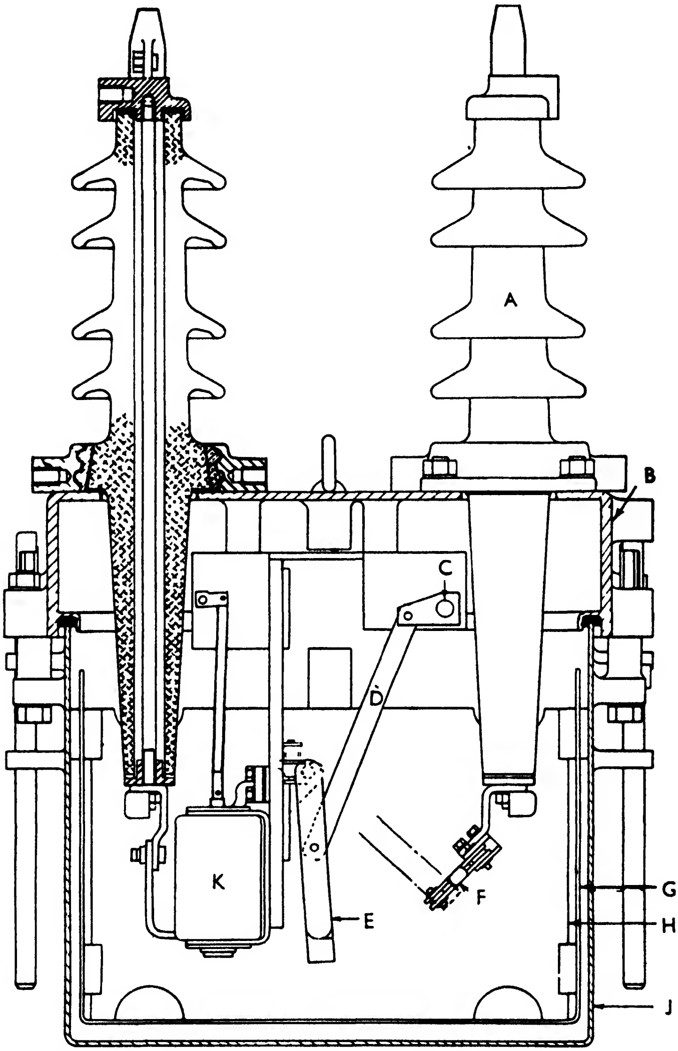


FIG. 18-36.—*Connection diagram for closing device (A. Reyrolle & Co. Ltd.).*

so that the armature returns to the open position under spring action. In this position the auxiliary contacts reclose and the magnet is re-energised to give a further charge to the closing spring. The sequence is repeated until the latter is fully charged, approximately seven strokes being required for the purpose and taking less than one second to complete.

While this charging of the closing spring is taking place a rotating cam is being moved into a position where, after the last charging stroke is completed, the spring is discharged thus closing the recloser contacts and opening the auxiliary contacts to de-energise the electromagnet. If, as a result of a permanent fault, the recloser completes its operating sequence, the auxiliary contacts are held open thus preventing any further charging of the closing spring and the recloser is locked open until reclosed manually by means of an external lever.

Sequence timing is by means of an oil dashpot which, for the instantaneous operations, is by-passed due to the opening of a piston valve. Thus the position of this valve determines whether the operation shall be instantaneous or time-delayed and its position is controlled by a sequence cam which moves whenever the recloser opens. The sequence cam indexes every opening operation and another cam on the same shaft operates a pull-rod controlling the position of the piston valve. Thus, by adjusting the position of these cams relative to each other, the required number of instantaneous and/or delayed operations can be selected.



A. BUSHING
B. TOP PLATE
C. OPERATING SHAFT
D. B.P. LINK
E. MOVING CONTACT
F. FIXED CONTACT
G. TANK LINING
H. PHASE BARRIER
J. TANK
K. SERIES COIL TIMING DEVICE (SEE FIG. 18-38.)

FIG 18-37.—*Sectional view of automatic sectionaliser* (*A. Reyrolle & Co. Ltd.*).

It will be seen from the part sectional view in Fig. 18-35 that ring type current transformers can be fitted over the recloser bushings and thus enable earth-fault protection to be included if required. This operates on

the core-balance principle and employs a rectifier-operated moving-coil relay which is also accommodated within the recloser. When operating on earth-fault, the recloser opens instantaneously throughout the predetermined number of operations to lock-out, i.e. no delayed tripping is allowed for.

We have noted on page 628 that where fuses are not employed for one reason or another in spur lines, an alternative is to employ an automatic sectionaliser, a device which is in effect an oil switch designed to isolate a faulty circuit after a preselected number of opening and closing operations of the protecting recloser, as shown in the operating cycle diagram Fig. 18-30. The interior of such a sectionaliser is shown in Fig 18-37.

This switch is closed manually by means of an external lever suitable for pole-operation, and is prepared for opening by the passage of fault current through a series coil tripping device operated in conjunction with an associated protecting recloser. The energy for operating the sectionaliser is derived from a manually operated spring-charged mechanism which causes the sectionaliser to open when a roller latch is broken by movement of the series coil trip rods.

The design of the series coil timing device is unique in that it must employ a form of dashpot which allows a predetermined number of fault-current pulses to flow through the coil before tripping occurs, i.e. each of the 3 pulses shown at (a) in Fig. 18-30 have to be carried before the sectionaliser opens.

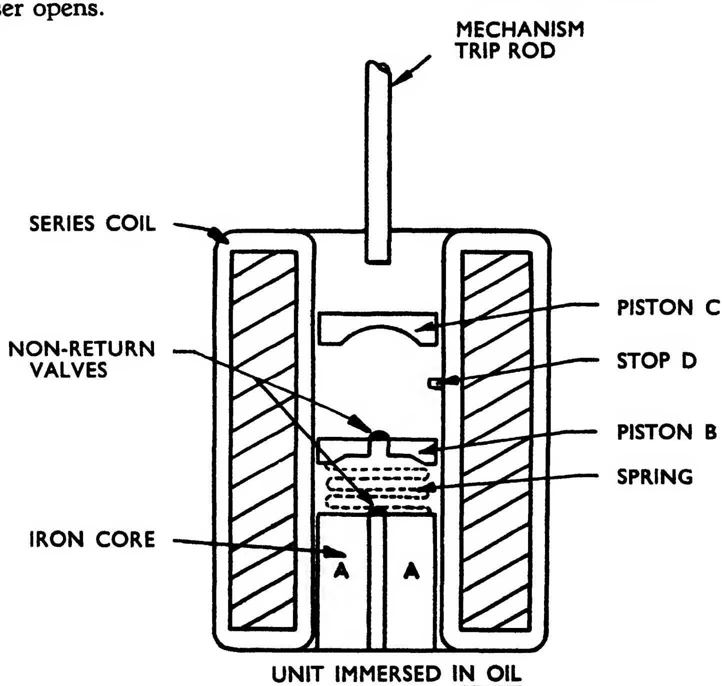


FIG. 18-38.—*Series coil timing device for automatic sectionaliser (A. Reyrolle & Co. Ltd.).*

Fig. 18-38 shows how this is achieved, using an electromagnet A which, when energised, attracts a piston B against the action of a spring. The piston B is fitted with a non-return valve such that when the piston is attracted downwards, oil flows from the underside to the top side, but when the piston is released by the electromagnet and is travelling upwards under the action of the spring, oil cannot return to the underside but instead forms a column which raises the position of piston C. This operation is repeated each time the fault current comes on and is switched off by the action of the associated recloser with the result that after the predetermined number of operations the piston C is raised sufficiently to operate the trip rod. If the fault is transient and is cleared by the recloser, the current pulses cease and piston C will reset by gravity on to its stop D. Facilities are provided whereby the number of pulse operations to cause tripping can be varied, this adjustment being made by raising or lowering the trip rod in relation to piston C.

POLE-MOUNTING CIRCUIT-BREAKERS

The fuse is an economical form of outdoor switching unit but is of somewhat limited application in so far as current ratings are concerned. For example, the expulsion type as described has maximum ratings of 75 and 50 amperes respectively for slow or fast blowing elements. In the cartridge type (current limiting) the range is higher at the lower voltages, ratings of 400 amperes being possible at 2·4 kV for example. In the fuse-switch unit, the fuse-link ratings range from 100 amperes maximum at 3·3 kV to 60 amperes at 11 kV.

When such limitation are of importance, an alternative but yet economical outdoor switching unit is the pole-mounted oil circuit-breaker, some constructional features of which have been noted in Chapter VI. Applied to pole-mounting as seen in Fig. 18-39 this breaker is operated from ground level by means of a simple hand lever mechanism through a chain drive. It can be arranged for automatic reclosure by means of the weight seen in Fig. 18-39 carried on the chain, standard practice being to provide for three reclosures at predetermined (adjustable) intervals and then to lock out.

Although primarily intended for pole-mounting, this type of circuit-breaker can equally well be mounted on a suitable frame on the floor and in this way used to control a power transformer, the breaker and the transformer being combined as a unit with a metal trunking to accommodate the inter-connections.

OIL SWITCH UNITS

Where automatic protection is not required, e.g. overload or earth fault, the load-breaking fault-making oil switch can often be used with economy. The requirement that the switch must be capable of "fault-making" is necessary in that occasions may arise when, unknown to an operator, a fault (short-circuit) exists on the controlled circuit at a time when he goes to close the switch. To make a design suitable for this duty and that of load-breaking, the opening and closing mechanisms should be such as to make the speed of opening or closing quite independent of the operator.

A design of this type is that shown in Fig. 18-40, the operating mechanism being of the spring-assisted type.

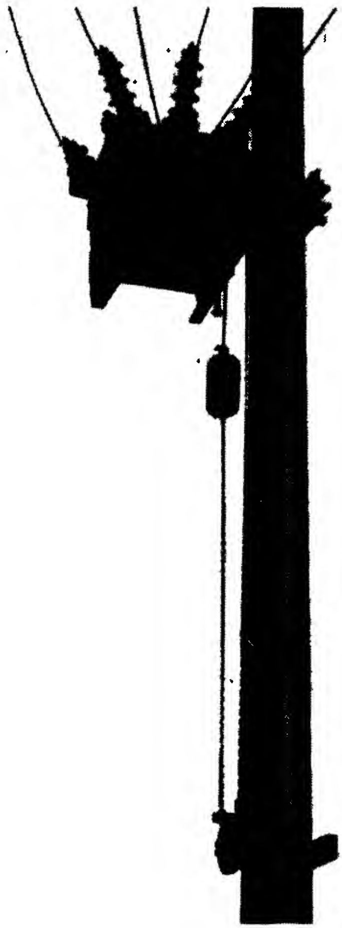
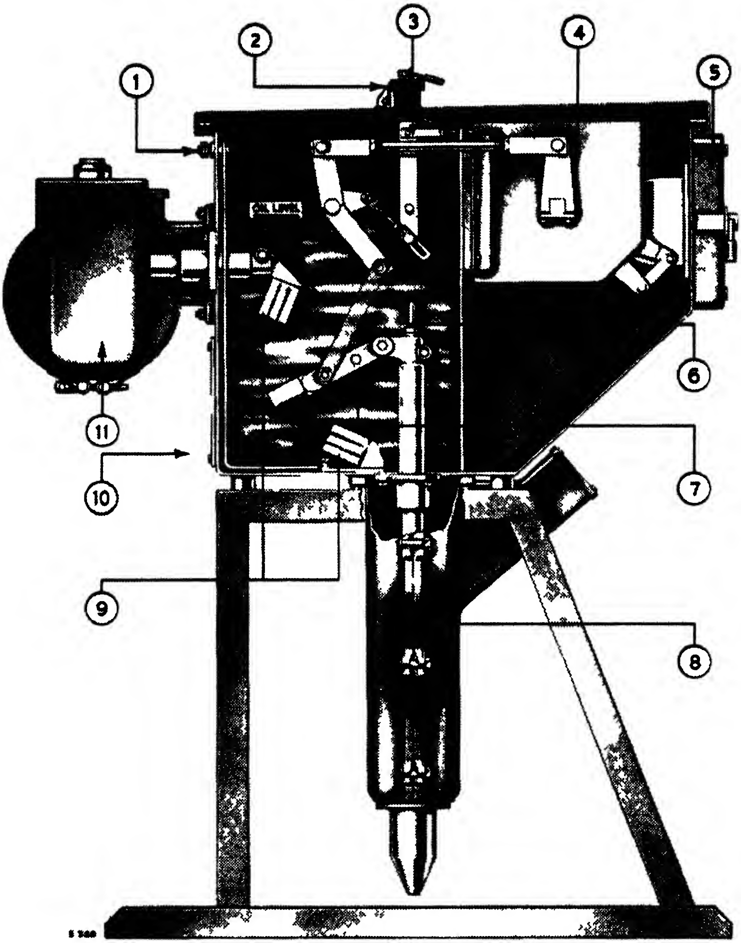


FIG. 18-39.—*Typical pole-mounting oil circuit-breaker. (Johnson & Phillips Ltd.).*



1	EARTH TERMINAL	6	CABLE TEST CONTACT
2	TEST ACCESS COVER	7	MOVING CONTACT
3	TEST SPIKE INTERLOCK	8	CENTRE-SPLIT CABLE BOX
4	OPERATING MECHANISM	9	FIXED CONTACTS
5	OPERATING HANDLE WITHIN ESCUTCHEON COVER	10	SWITCH ACCESS COVER
		11	BUSBAR CHAMBER

FIG. 18-40.—*Outdoor type oil-switch unit 400 amp 11 kV (Brush Electrical Engineering Co. Ltd.).*

The oil-switch is a single break type having "on", "off" and "earth" positions and the operation to the different positions is achieved by a single operating handle which must be placed in one of two slots, only one being accessible at a time. By this means it is impossible to go direct from the "on" position to "earth" or vice versa, as the operator must stop at the "off" position to change the handle location. As in other units of this type described earlier in relation to indoor switchgear, facilities are provided for testing the incoming cable with the switch in the "off" position but only after the cable has been first earthed.

As indicated, an oil switch is intended for load-breaking, i.e. 400 amperes, and fault-making. The switch described has a making capacity of 33·4 kA (peak) at both 6·6 and 11 kV.

METALCLAD OR METAL-ENCLOSED (PACKAGED) SWITCHGEAR.

So far, we have considered types of outdoor gear where the protection afforded to a circuit is of the simplest form, e.g. fuses or magnetic overloads, or without any protective gear in the case of the oil switch. Such types cannot meet all service requirements and designs have therefore been introduced which afford many of the facilities available in indoor metalclad types but made entirely suitable for outdoor use in electrically exposed situations and employing oil circuit-breakers.

In this section we shall note designs which embrace a voltage range up to 33 kV, noting first an 11 kV design as shown in Figs. 18-41 and 18-42.

This design is interesting in several respects, particularly the feature which eliminates the need to move the circuit-breaker for isolation purposes as in the drop-down or draw-out types noted for indoor applications. Isolation in this case is achieved by two oil-immersed isolators contained in separate compartments immediately above the circuit-breaker, as seen in Fig. 18-42. Any necessary current transformers are accommodated in a further oil (or compound) filled chamber and the busbars are in a compound-filled chamber. Thus there are no electrical clearances in air, the fixed circuit-breaker having eliminated the need for air-insulated isolating spouts. It will be noted from Fig. 18-42 also that the isolating switches have no "off" positions, being provided only with "on" or "earthed" positions. Both isolators are operated simultaneously and are interlocked so that they can only be moved from "on" to "earth" after the oil circuit-breaker has been opened, thus eliminating the possibility of breaking or making load current on the isolators or of making on to a fault. Another interlock ensures that the oil circuit-breaker tank cannot be removed unless the isolators are in the "earth" positions.

Provision is made at the isolator operating mechanism gate whereby independent operation of the isolators can be made when it is desired to earth either the feeder or the busbars through the circuit-breaker, and cable testing facilities are available with suitable precautionary interlocks.

A development of this unit is that shown in Fig. 18-43 where the enclosure is extended to take outdoor through-bushings so that direct connection with an overhead line can be made.

The units shown are available for 400 or 800 ampere current rating, with breaking capacities of 350 MVA at 11 kV and 250 MVA at 6·6 kV.

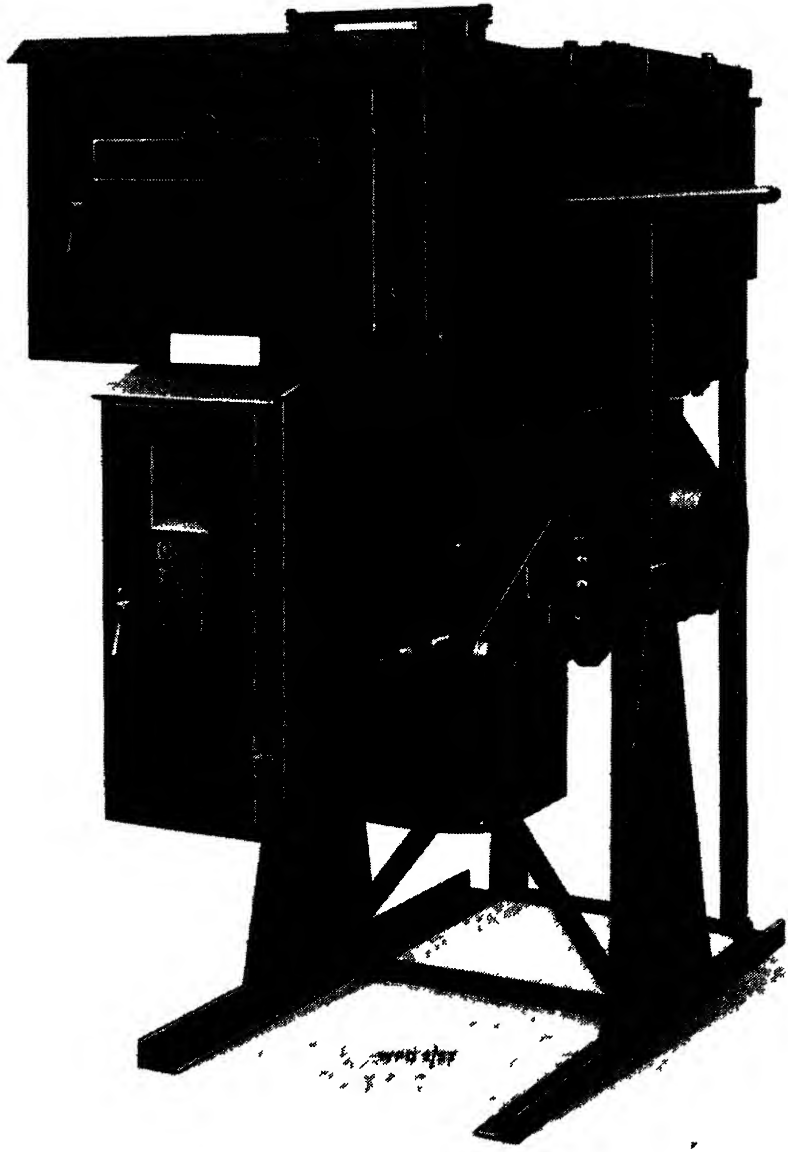


FIG. 18-41.—*Outdoor metalclad oil circuit-breaker unit (Long and Crawford Ltd.).*

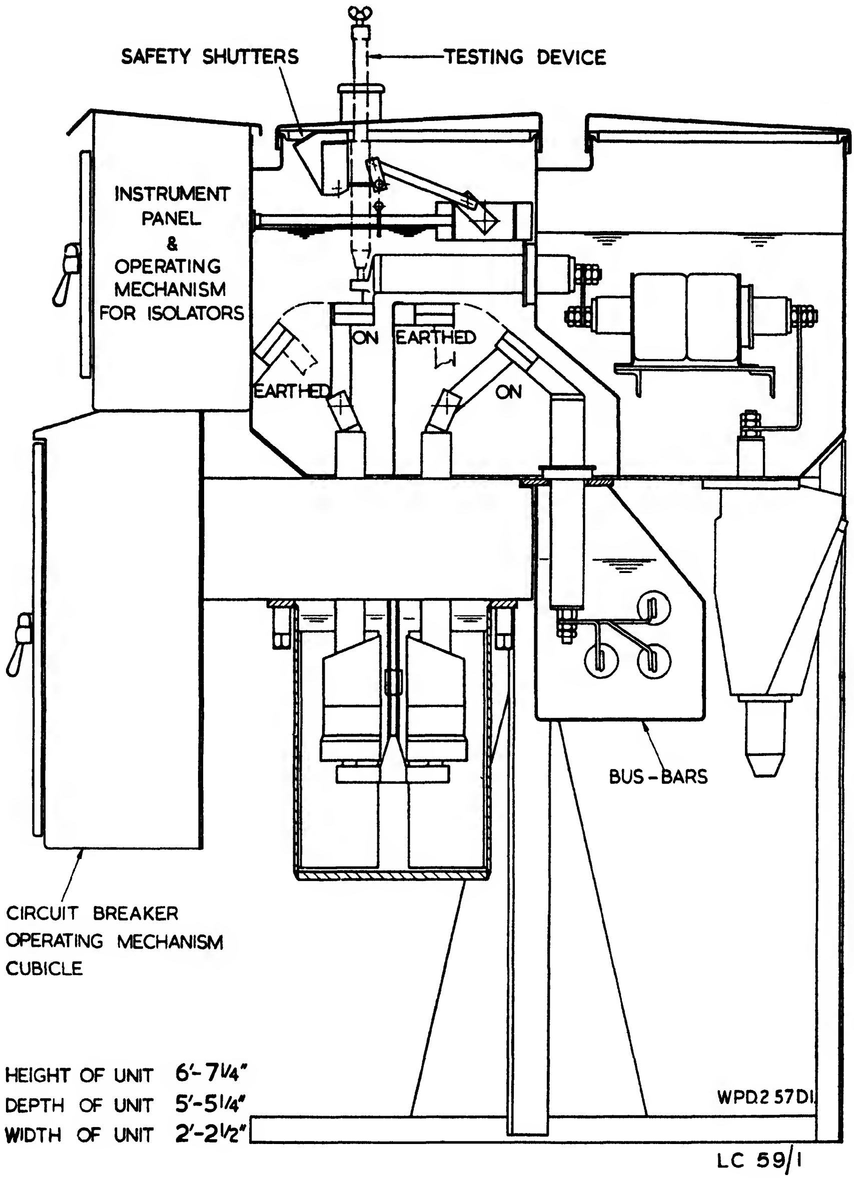


FIG. 18-42 —*Cross-section of outdoor metalclad unit in Fig. 18-41. (Long and Crawford Ltd.).*

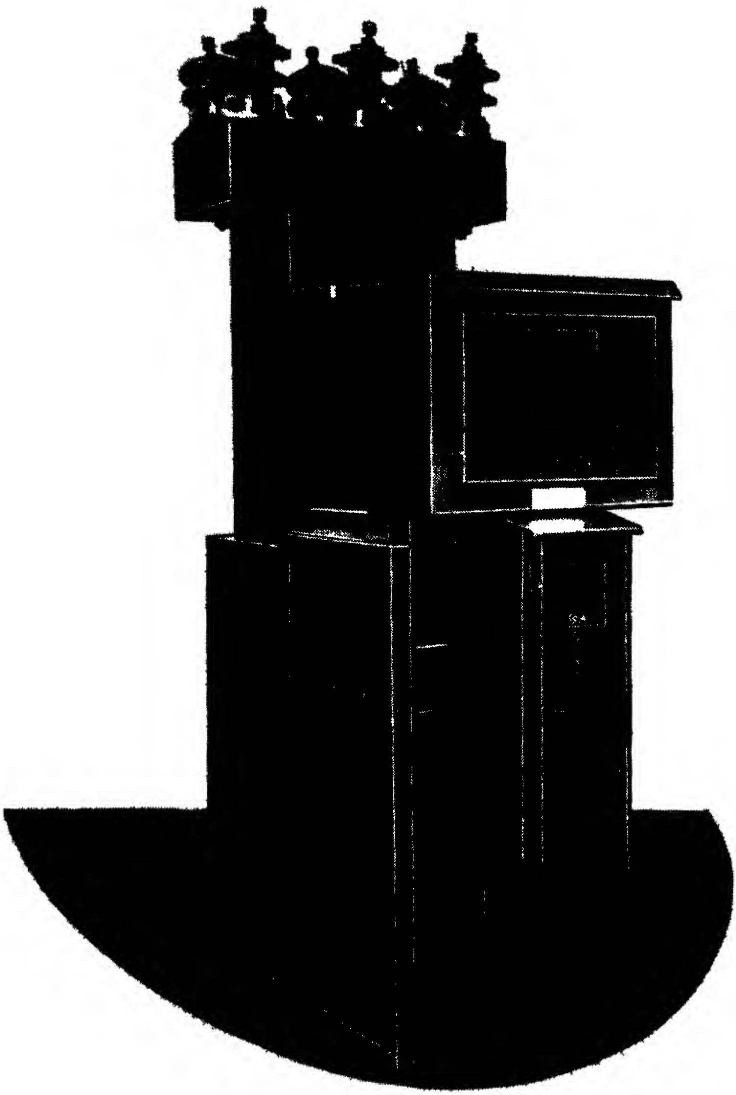


FIG 18-43 —*Outdoor metalclad oil circuit-breaker unit with extended current transformer chamber to accommodate through-bushings* (*Long & Crawford Ltd*)

In Chapter X we have noted some details of a range of metalclad switchgear for outdoor service in which the principle of inverted vertical isolation is employed. This gear includes a circuit-breaker in which the "Caton Arc-Trap" described in Chapter VI is used.

As we have seen in Figs 10-14 and 10-15, a weatherhood gives complete protection against the elements and a typical switchboard is shown in Fig. 18-44

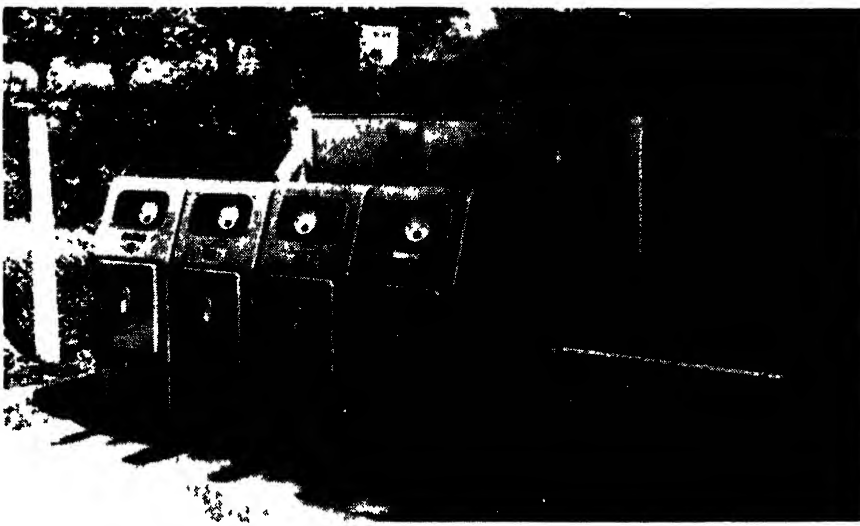


FIG 18-44—*A typical 4-panel 11 kV outdoor metalclad switchboard (Yorkshire Switchgear and Engineering Co. Ltd.).*

In this illustration a weatherproof cabinet is seen behind the main switchgear, this being installed to accommodate relays and metering equipment, telephone, etc.

Fig. 18-45 shows how, after the circuit-breaker has been raised (isolated) and the moving portion drawn forward, the weatherhood is hinged backwards to give access to the circuit-breaker, instruments, trip coils and associated details.

This type of gear is available for voltages in the range 415 volts to 22 kV and for use on systems with fault levels of 2·5 MVA to 500 MVA. Oil switches and fused switches of similar construction can be readily lined up with the circuit-breaker unit, one example having been previously noted in Fig. 10-15.

The same manufacturer has also developed a design of outdoor metal-clad switchgear for use on 33 kV systems with interrupting capacity up to 1 000 MVA. A typical unit is shown in Fig. 18-46(a) in which the steel roller shutter has been raised to show the circuit-breaker unit in its weather-proof housing.

In this design, horizontal isolation is employed, with the circuit-breaker at ground level in its service and isolated positions. After being isolated,

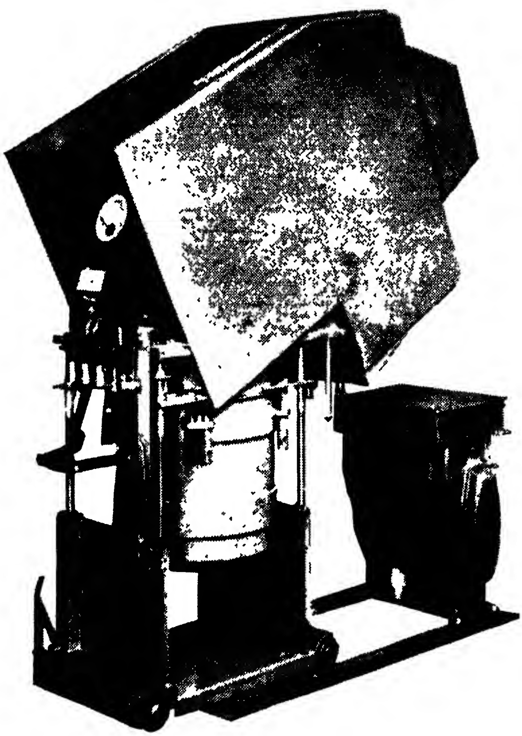


FIG. 18-45.—*Weatherhood raised to permit inspection of outdoor metalclad unit.* (*Yorkshire Switchgear and Engineering Co. Ltd.*).

the circuit-breaker can be raised vertically to a position where it can be reconnected for cable earthing, plugging in to test spouts, i.e. the circuit-breaker can be transferred from "service" to "cable earth".

Fig. 18-46(b) shows the contact system of the circuit-breaker with the "Caton Arc-Traps." The facilities of isolation, transfer to cable earthing, and maintenance are achieved by hydraulic operation with fully interlocked selector switches and push button control. The circuit-breaker closing mechanism comprises hydraulically actuated springs with electrical release.

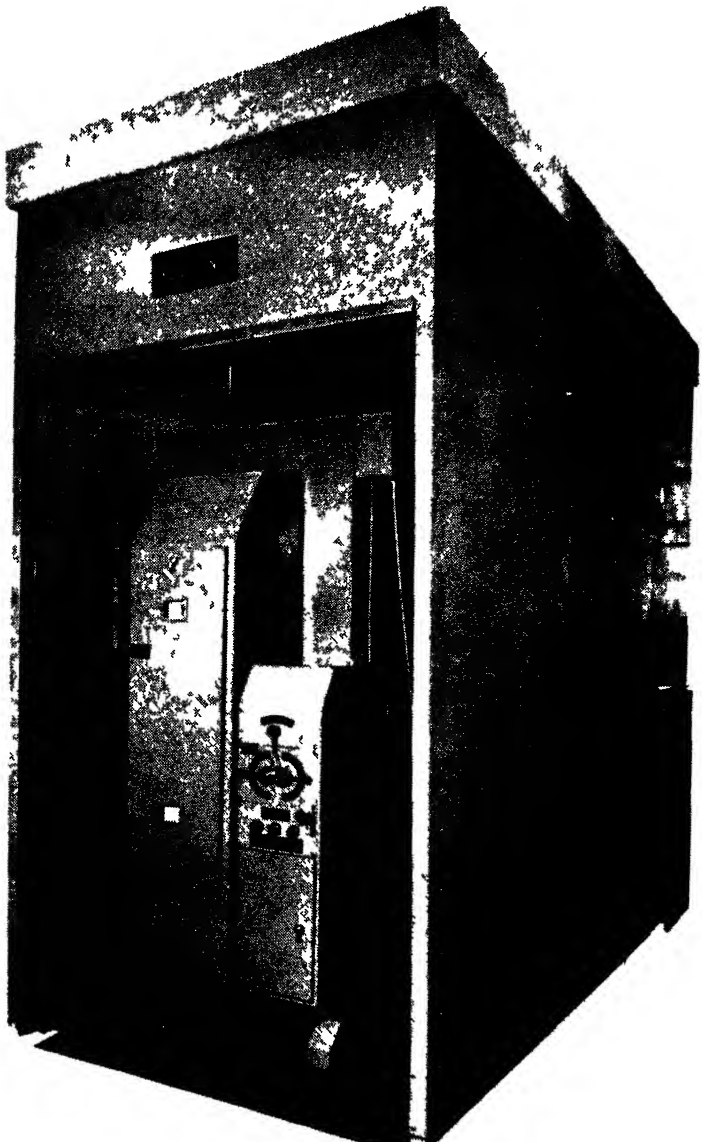


FIG. 18-46(a) —33 *kV metalclad outdoor switchgear View of complete unit with front shutters raised (Yorkshire Switchgear and Engineering Co Ltd).*

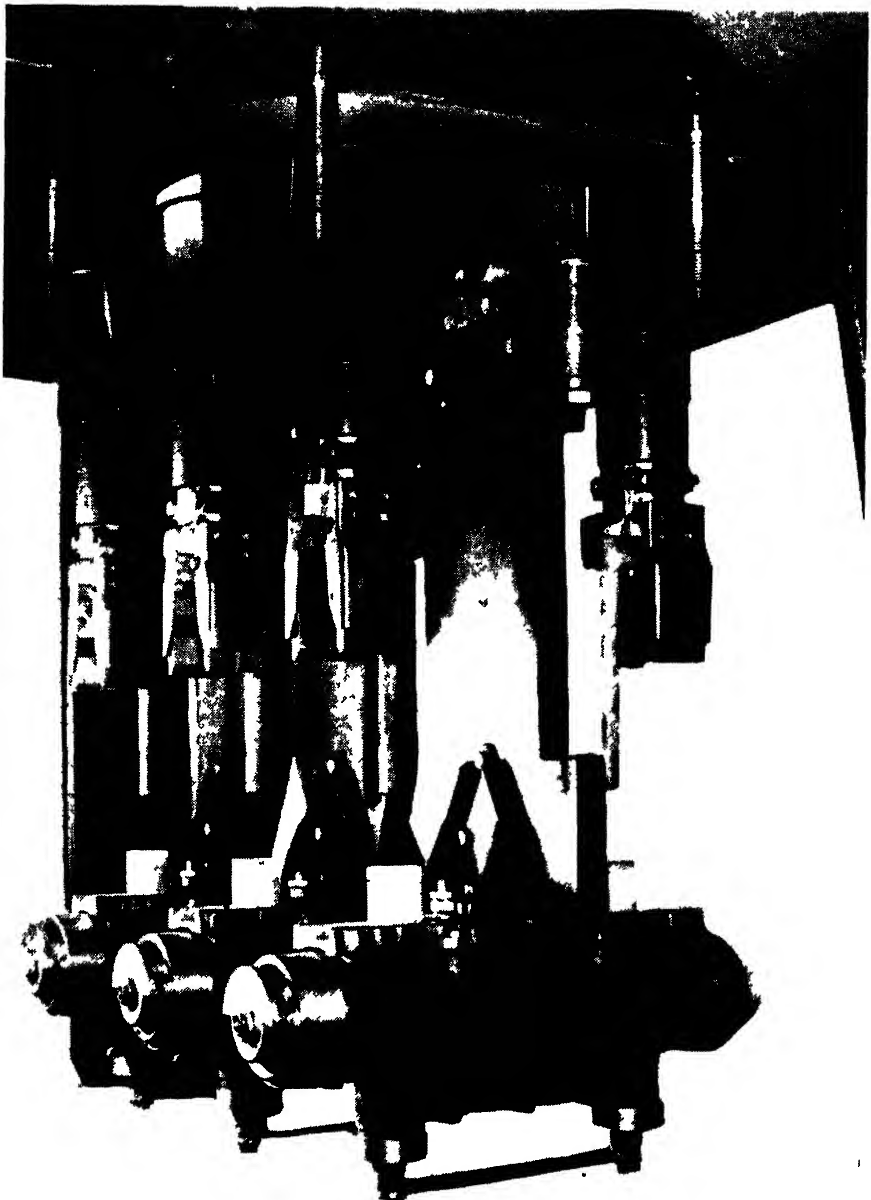


Fig. 18-46(b).—*Circuit-breaker with tank removed to show contacts and arc-traps (Yorkshire Switchgear and Engineering Co. Ltd.).*

Fig. 18-46(c).—*Circuit-breaker closing mechanism and controls* (*Yorkshire Switchgear and Engineering Co. Ltd.*).

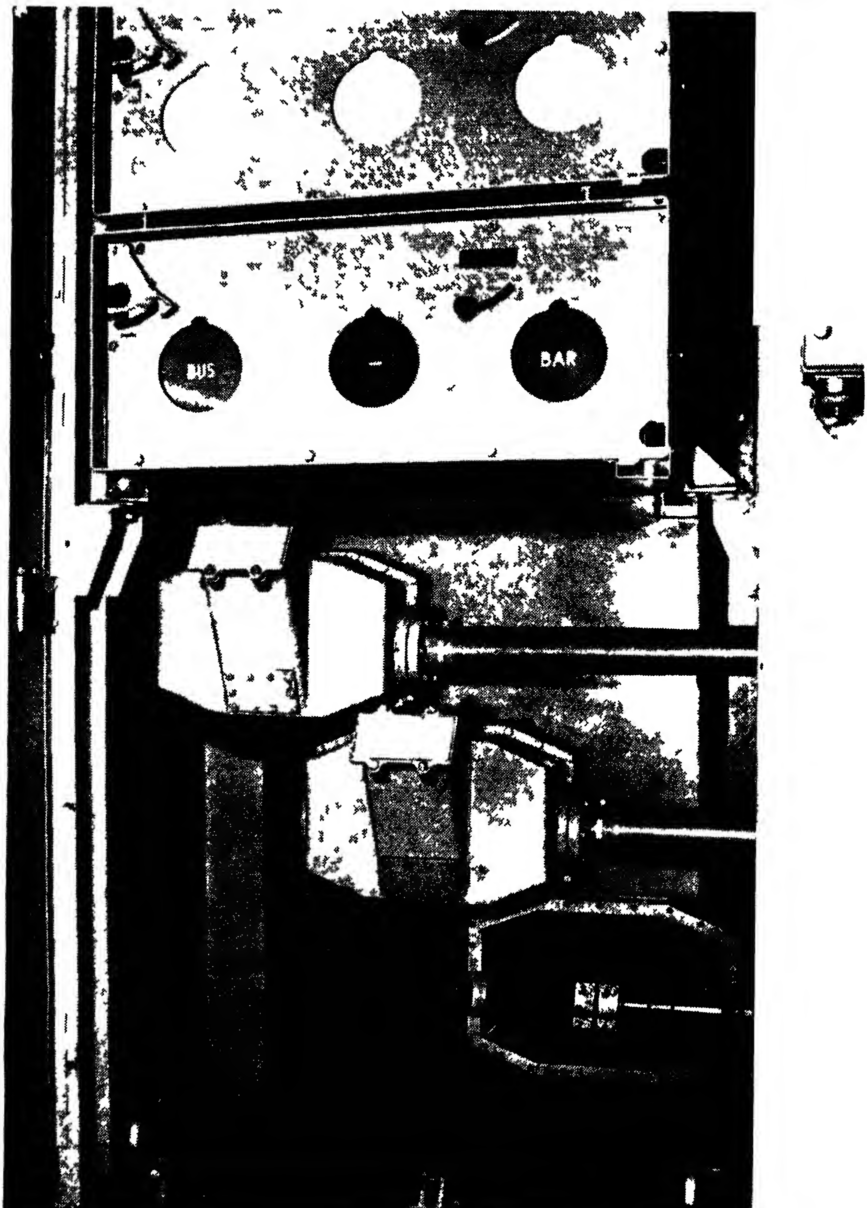


Fig 18-46(d) —*View of 33 kV busbars and busbar tee-off junction boxes (Yorkshire Switchgear and Engineering Co Ltd)*

Charging of the springs is by a small motor which can be connected to any convenient medium-voltage supply or to a 110 volt battery. The closing mechanism and other control facilities are shown in Fig. 18-46(c).

A feature of the design is that in the event of a supply failure, a hand pump is provided capable of carrying out the operational facilities. It can also be used for slow-closing of the circuit-breaker in the isolated position for maintenance and adjustment purposes.

The isolating plugs are epoxy sleeved condenser bushings with flexible resin in the annular space between the bushing and the outer sleeve. Condenser bushing type busbars are also employed, with compound-filled busbar/tee-off junction boxes, as shown in Fig. 18-46(d). This illustration also shows the busbar and cable plug orifice shutters which are independently operated and may be individually locked.

The range includes an oil switch of the load-breaking fault-making type. This switch is of the double-break type with a spring assisted closing mechanism for the main and earthing switches. It is possible to close the main switch by remote push button by using a small single phase motor to compress the springs in the closing mechanism.

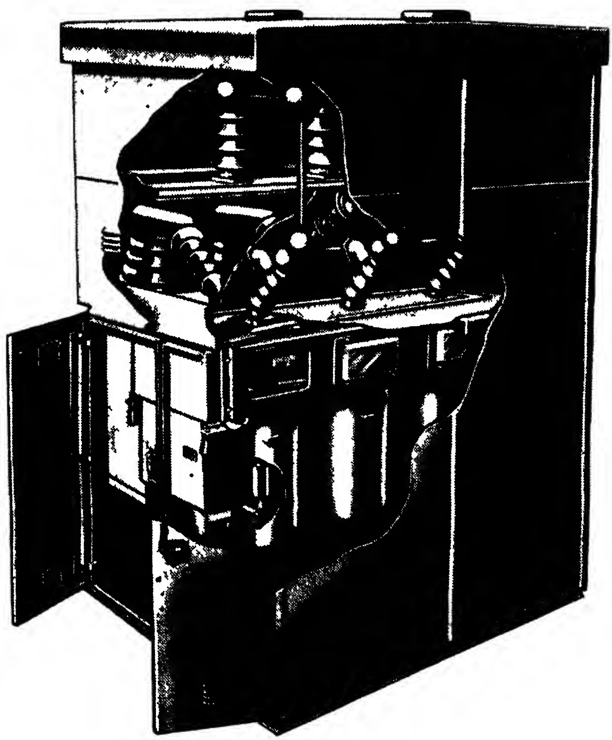


FIG. 18-47.—33 *kV outdoor metal-enclosed air-insulated switchgear unit (A. Reyrolle & Co. Ltd.).*

In another 33 kV design, shown in Fig. 18-47, a fixed circuit-breaker is employed, isolation being obtained by rotatable bushing isolators in the circuit-breaker top plate. These bushing isolators have two positions only, viz. "service" and "earth" and a full complement of interlocks to ensure correct sequential operation. As in another development we have noted earlier, the circuit-breaker tanks cannot be removed unless the circuit-breaker is isolated and *earthed* on both sides.

The circuit-breaker is completely phase-separated, each phase being contained in a separate oil tank and may be closed either by a spring or solenoid operating mechanism. Glass-fibre arc-control devices of the "Turbulator" type noted in Chapter VI are employed and the circuit-breaker has ratings of 750 and 1 000 MVA at 33 kV, with normal current ratings up to 2 000 amperes.

Facilities for cable earthing, cable testing and injection testing of protective gear are provided in this unit, the whole being contained within an integral structure to form a shelter, with full width access doors.

Metal-enclosed or packaged type switchgear is generally available up to 33 kV and derives its name from the fact that the metal enclosure affords

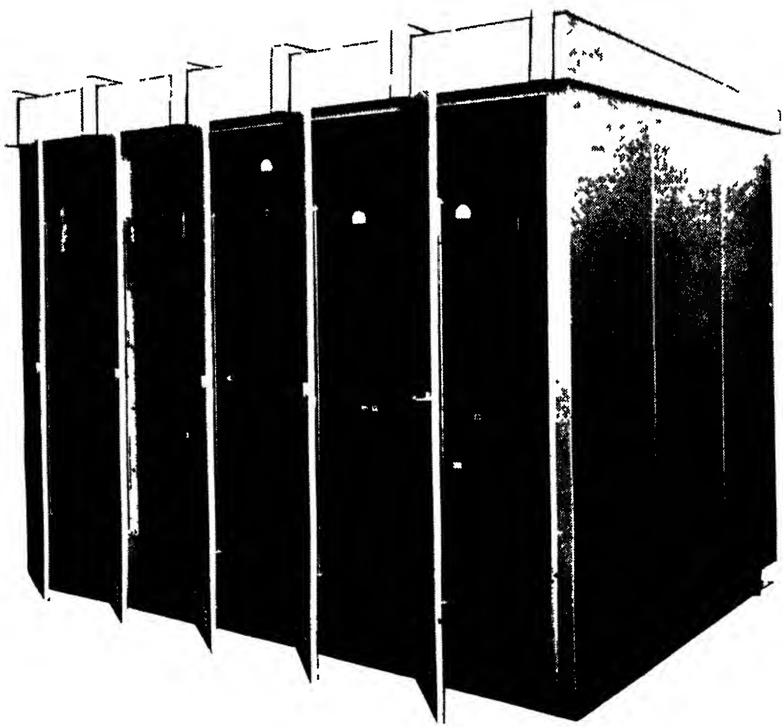


FIG. 18-48.—*Packaged substation for voltages up to 15 kV and with five circuit-breaker units of the vertical isolation type (A. Reyrolle & Co. Ltd.).*

the protection which would otherwise be given by a building, and that, in some cases the complete switchboard may be shipped to site without dismantling or in other cases (at 33 kV), elements of the whole will be shipped to site in such a manner that re-assembly is reduced to a minimum. In many ways this resembles the once popular kiosk except that the latter usually housed not only the high-voltage switchgear but also a small power transformer and low-voltage distribution fuse units, whereas in the packaged substation, only high-voltage gear is housed.

Typical of the type is that shown in Fig. 18-48, in which a 5-panel switchboard is seen behind the open access doors. Similar doors at the rear give access to the cable compartments.

For convenience of assembly and for shipment purposes, a long board of more than five units is subdivided into two or more lengths and reassembled as an entity on site. The space at the front of each unit provides a working gangway and is sufficient to permit withdrawal of a circuit-breaker carriage and to carry out maintenance on it under cover.

A problem with all enclosed gear of this type is that of condensation. In the design illustrated this is eliminated by treating the underside of the roof with thermal insulation and by ensuring constant air circulation inside

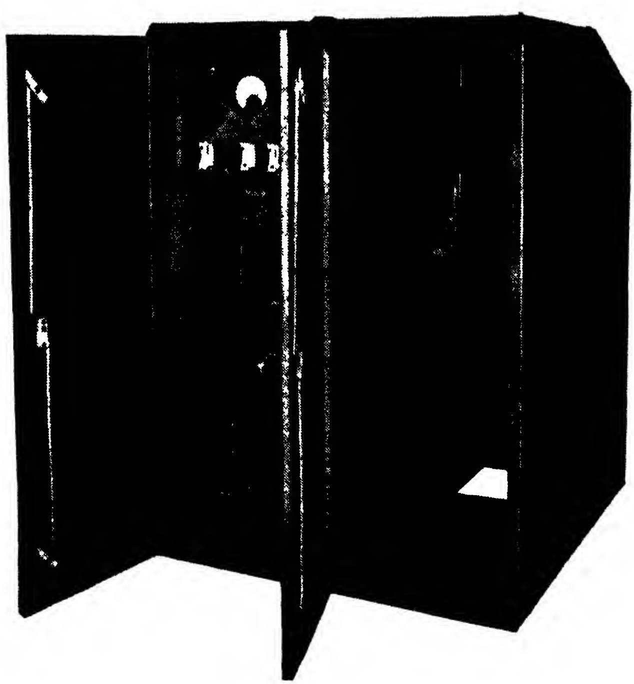


FIG. 18-49.—*Low type packaged substation housing an oil circuit-breaker unit and an oil switch for voltages up to 11 kV.*
(South Wales Switchgear Ltd.).

the enclosure through rodent-proof louvres at the base of each door and under the eaves. A further preventive measure consists of priming and finish painting in stoved epoxy resin heat-reflecting aluminium.

In another range of packaged substation two forms have been developed, one, shown in Fig. 18-49, being a low level design for housing vertical isolation oil circuit-breakers up to 1 200 ampere rating and/or load-breaking fault-making oil switches of 400 ampere capacity, for voltages up to 11 kV, the whole being fully extensible on either side. In a second design known as the "aisle" type a single access door at the end of the substation affords access to an operating and servicing area in front of the circuit-breaker units, as shown in Fig. 18-50.

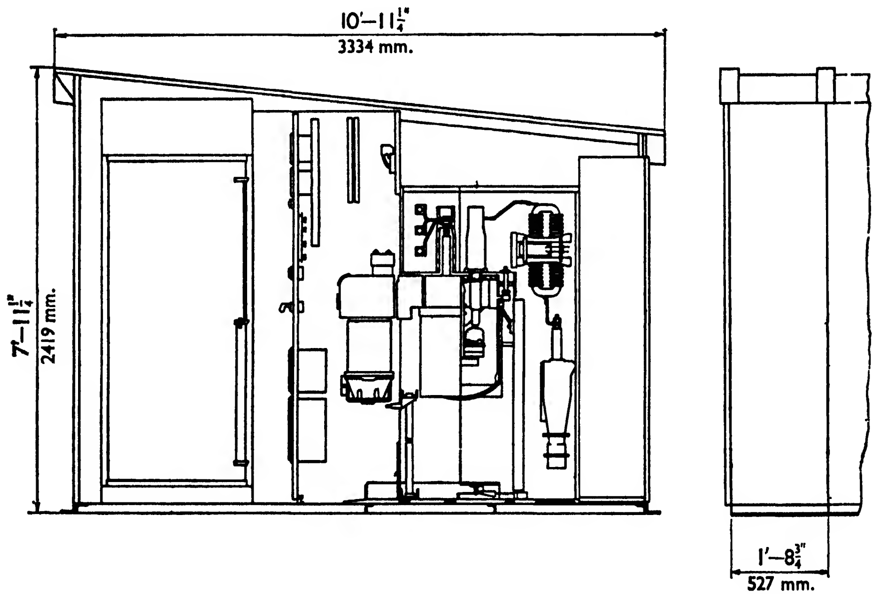


FIG. 18-50.—*Sectional view of packaged substation 13·8 kV 500 MVA of the "aisle" type (South Wales Switchgear Ltd.).*

In this latter design access to each individual unit from the aisle involves the opening of a further door which acts as an instrument and control panel, as shown in Fig. 18-50. The aisle is of such width as to allow withdrawal of a circuit-breaker unit under cover for servicing or other purposes. If required for connection to overhead lines, roof bushings can be included,

FIG. 18-51.—*Two 14-panel 33 kV single busbar switchboards of the packaged type at the East Kirby Switching Station of the East Midlands Electricity Board. (South Wales Switchgear Ltd).*

while the connections between a circuit-breaker unit and an outdoor power transformer can be made in an interconnecting trunk.

At 33 kV, package type switchgear can lead to very considerable saving in space, and requires only a fraction (probably about one-tenth) of the area necessary for open type outdoor gear. An interesting example of this space economy is that shown in Fig. 18-51, where two 14-panel switchboards combine to complete a 28 unit switching station in an area of 20 yards by 34. The design of unit employed in this illustration is noted in more detail in Fig. 18-52 a feature being that the unit is completely air-insulated except for the oil used in the circuit-breaker and voltage transformer tanks and all insulation exposed to air is of porcelain with creepage paths to earth generally comparable with 44 kV outdoor practice. Another feature is that although the circuit-breaker is arranged for vertical isolation, there are no orifice insulators, the plug and socket isolators at the circuit-breaker terminals being completely unshrouded, as seen in Fig. 18-53.

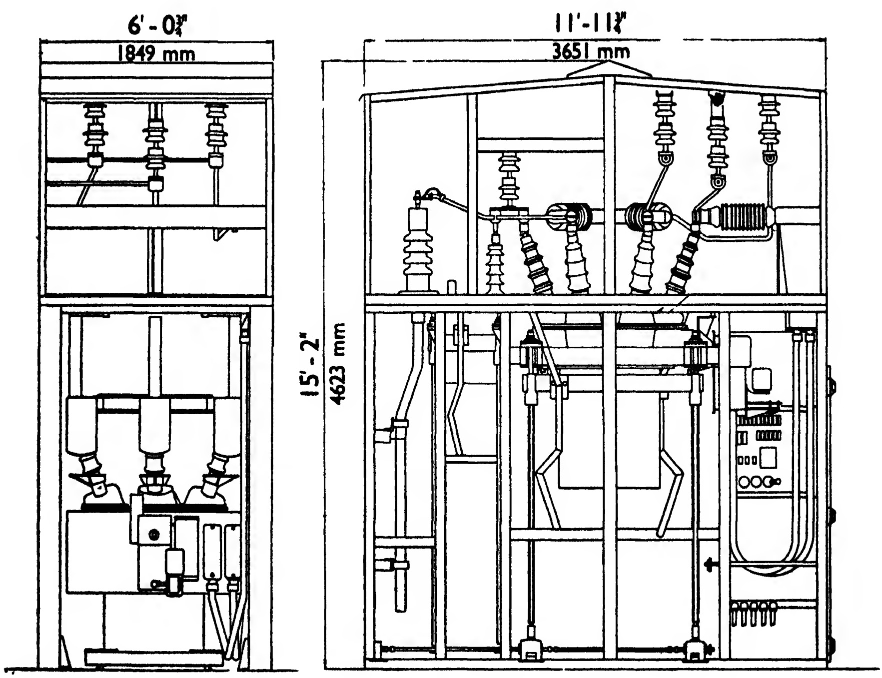


FIG. 18-52.—*Sectional view of 33 kV packaged switchgear unit with single busbars. (South Wales Switchgear Ltd.).*

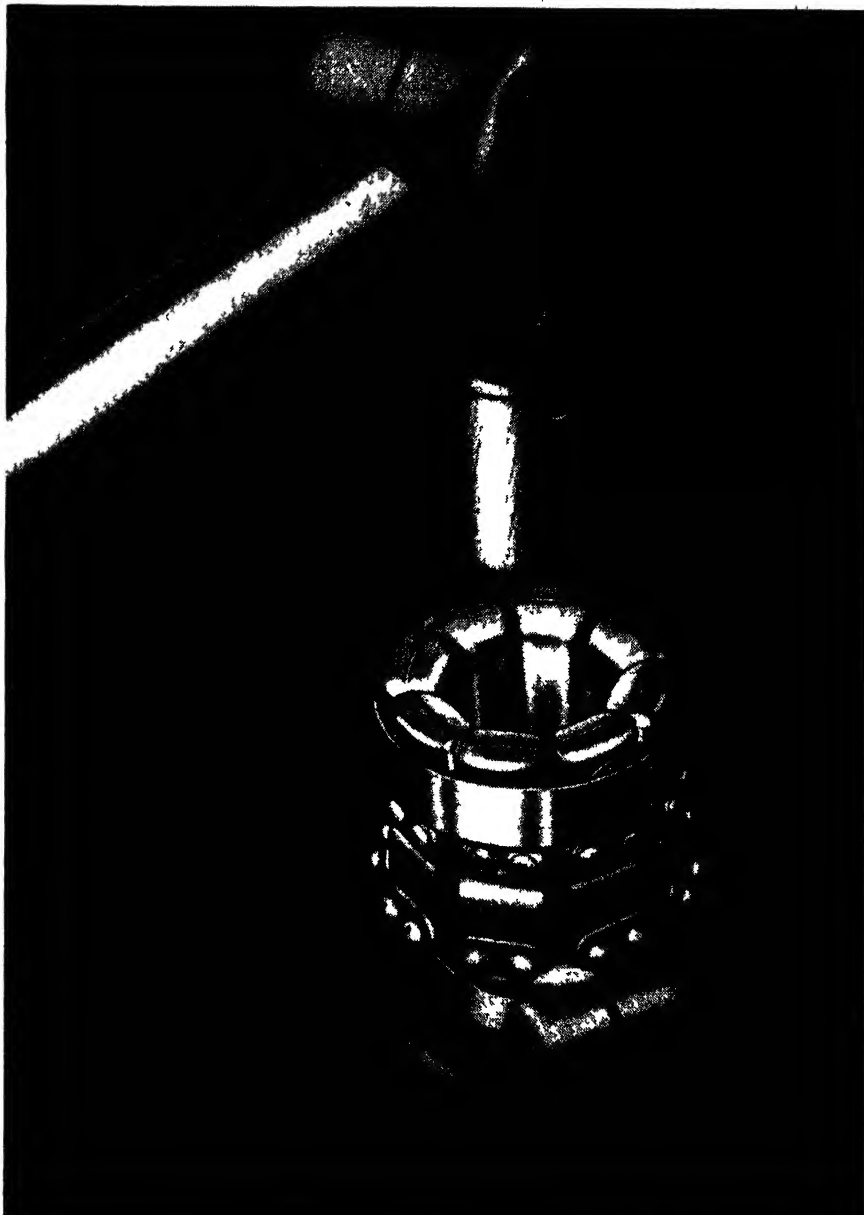


FIG. 18-53.—*Plug and socket isolators between circuit-breaker and busbars. (South Wales Switchgear Ltd.).*

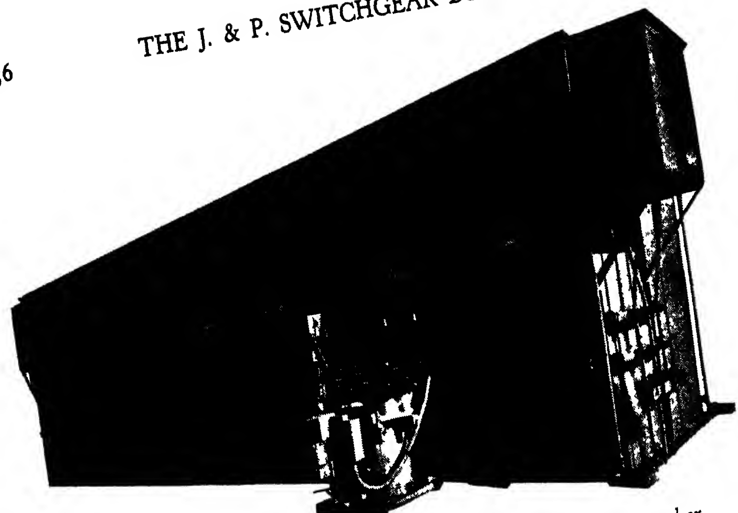


FIG. 18-54.—33 kV packaged switchgear with one circuit-breaker isolated and withdrawn from enclosure (South Wales Switchgear Ltd.)

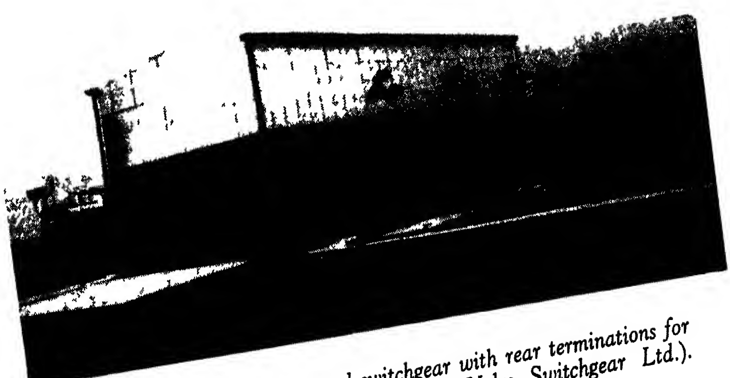


FIG. 18-55.—33 kV packaged switchgear with rear terminations for connection to overhead lines. (South Wales Switchgear Ltd.).

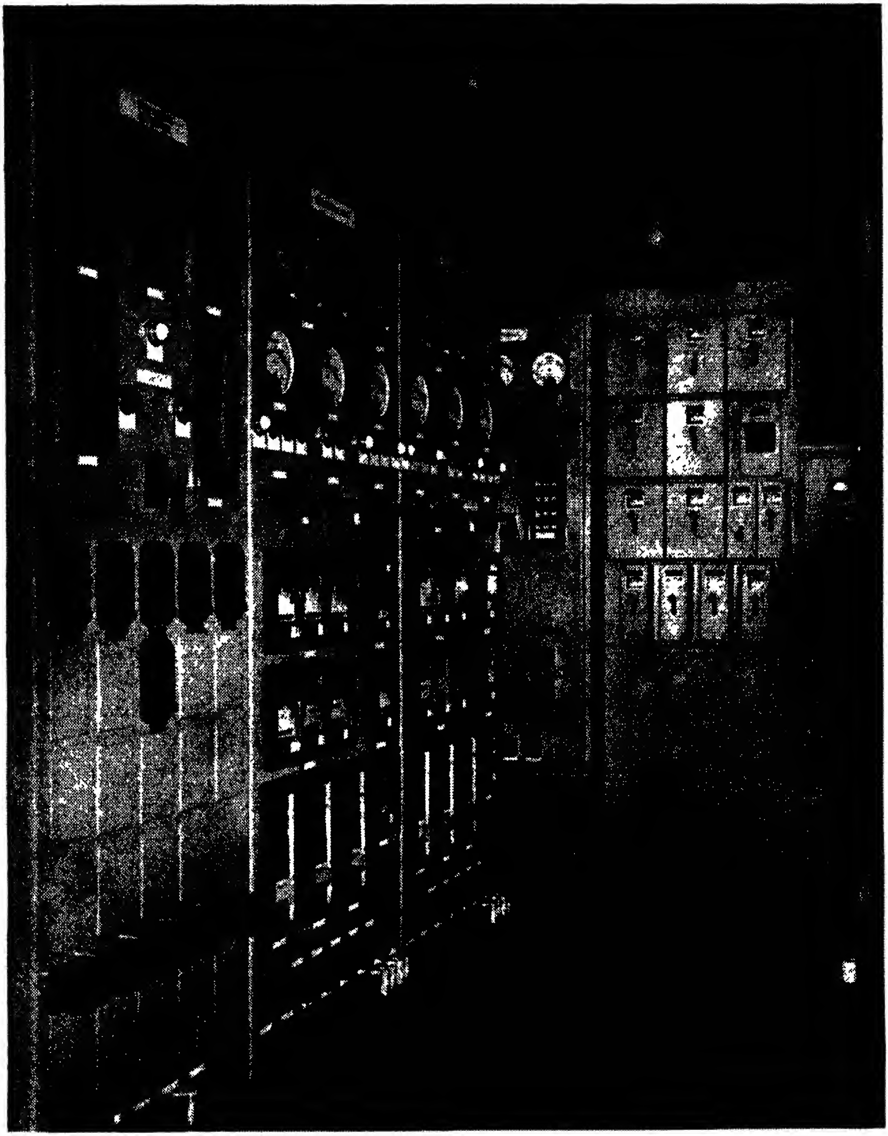


FIG. 18-56.—*Self-contained control room forming part of a 6-unit 33 kV packaged substation. (South Wales Switchgear Ltd.).*

Normal servicing of the circuit-breaker can be carried out within the housing but space must be left in front of the units for complete removal should this be necessary, as shown in Fig. 18-54.

By suitably increasing the back to front dimension and the height, a duplicate busbar arrangement is possible, the choice of busbar in service being on the transfer breaker principle as described in Chapter XIII. Where circuits are for controlling overhead lines, through-bushings can be fitted either at the rear of units or in the roof. An example of the former is noted in Fig. 18-55.

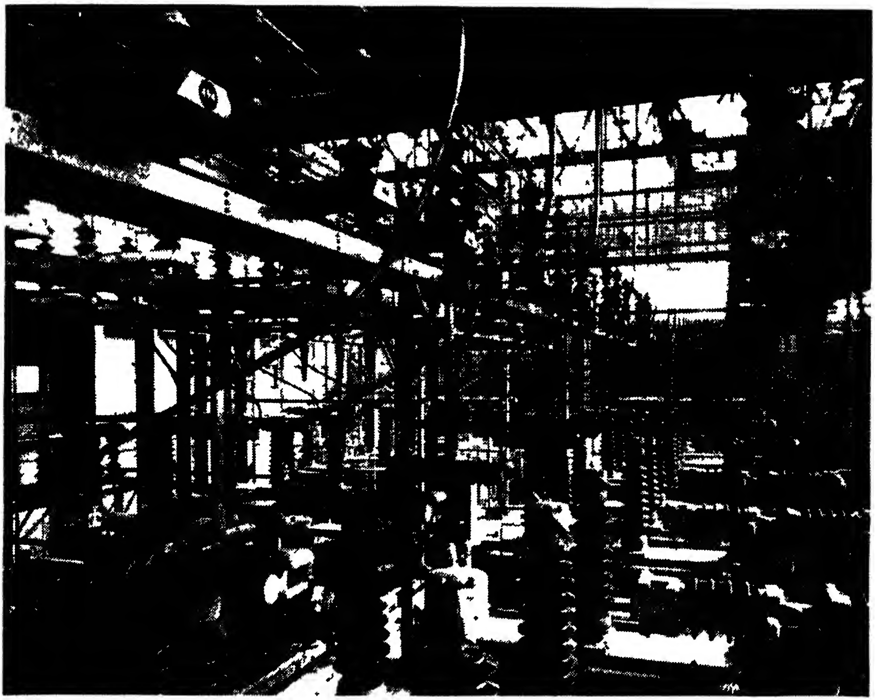


FIG. 18-57.—132 *kV indoor switching station at the C.E.G.B. Nuclear Power Station at Hunterston, with air-blast circuit-breakers at* 3 500 *MVA.* (*Associated Electrical Industries Ltd.*).

For the remote control of the circuit-breakers and for accommodating indicating instruments protective relays and other miscellaneous apparatus, e.g. battery, one or more of the compartments can be set aside to act as control room. Such a control room is that shown in Fig. 18-56.

The gear as described is rated up to 1 000 MVA at 33 kV and with normal current ratings up to 2 000 amperes. Current-breakers of 1 500 MVA rating can also be included in the same frame size.

MAJOR SWITCHING STATIONS OR SUBSTATIONS

With increasing voltage and interrupting capacity it becomes necessary to contemplate a switchgear installation of the completely outdoor type with no protective shelter. This is usually the condition for voltages of 66 kV up to 400 kV for which the outdoor types of bulk-oil, small-oil-volume, or air-blast circuit-breaker as discussed in Chapters VI, VII and VIII will be used.

It may be noted however that outdoor substations may on many occasions be used for voltages below 66 kV and, conversely, some higher voltage installations may be of the indoor type In this latter respect we have noted in Chapter VIII, Fig. 8-19, an example where 66 kV air-blast circuit-breakers have been installed in individual block houses. A very recent example of an indoor switching station at 132 kV is that shown in Fig. 18-57, and even more recently, details have been given of indoor substations at 275 kV.*

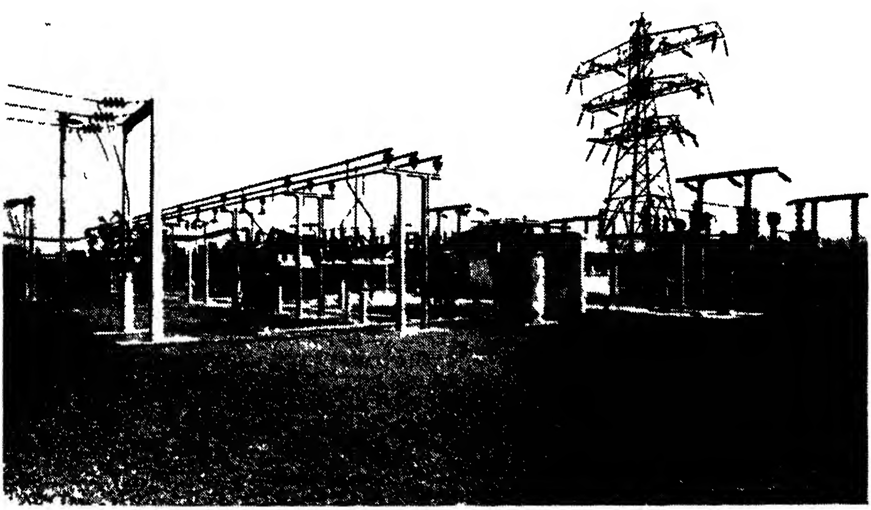


FIG. 18-58.—33 *kV outdoor substation North of Scotland Hydro-Electric Board, Coupar-Angus, Perthshire. (Brush Electrical Engineering Co. Ltd.).*

* *See Electric Times pp 919–923, 20th June, 1963.*

It must be remembered that in the outdoor station, the surfaces of all the many insulators are subject to atmospheric pollution and under bad conditions may require frequent cleaning if flashovers are to be prevented. It is for reasons such as this that development of the outdoor metalclad or metal-enclosed types (within voltage limits) has proceeded apace. It is also one of the reasons why, in outdoor designs, the "low-level" type is preferable to the alternative "high-level" type. In the former, the various component items are all mounted as near to ground level as electrical clearances permit, thus

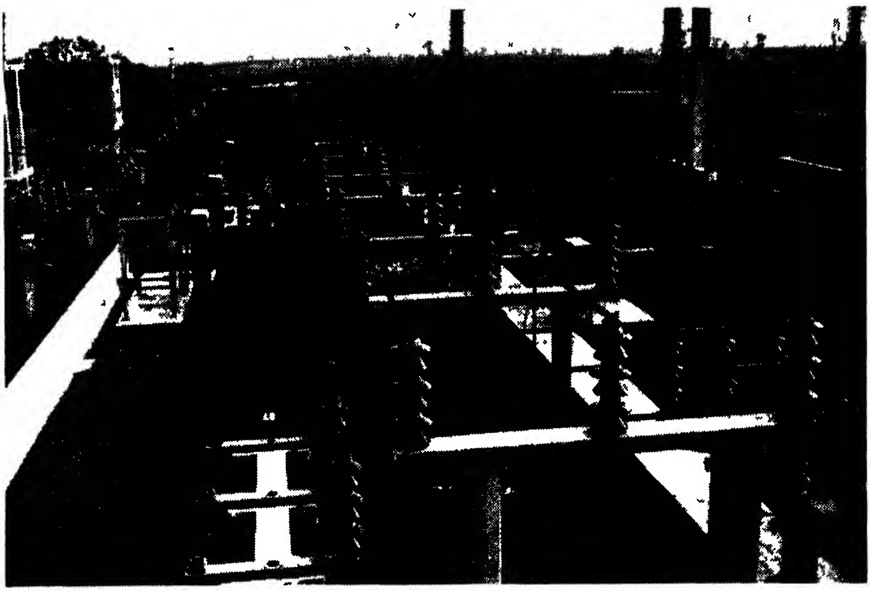


FIG 18-59.—66 *kV outdoor substation Yorkshire Electricity Board, Driffield. (English Electric Co. Ltd.).*

easing the problem of cleaning and maintenance considerably. Typical stations of the low-level type are shown in Figs. 18-58 and 18-59, from which will be noted the extensive use of concrete supporting structures, but this is not essential, as lattice structures in steel can be used as shown in the examples Figs. 18-60 and 18-61, the former being an example of substation employing oil circuit-breakers, the latter one employing air-blast circuit-breakers.

FIG. 18-60.—66 *kV outdoor substation for the Sengulam Hydro-Electric Power Station of the Government of Travancore & Cochin, India. (English Electric Co. Ltd.)*

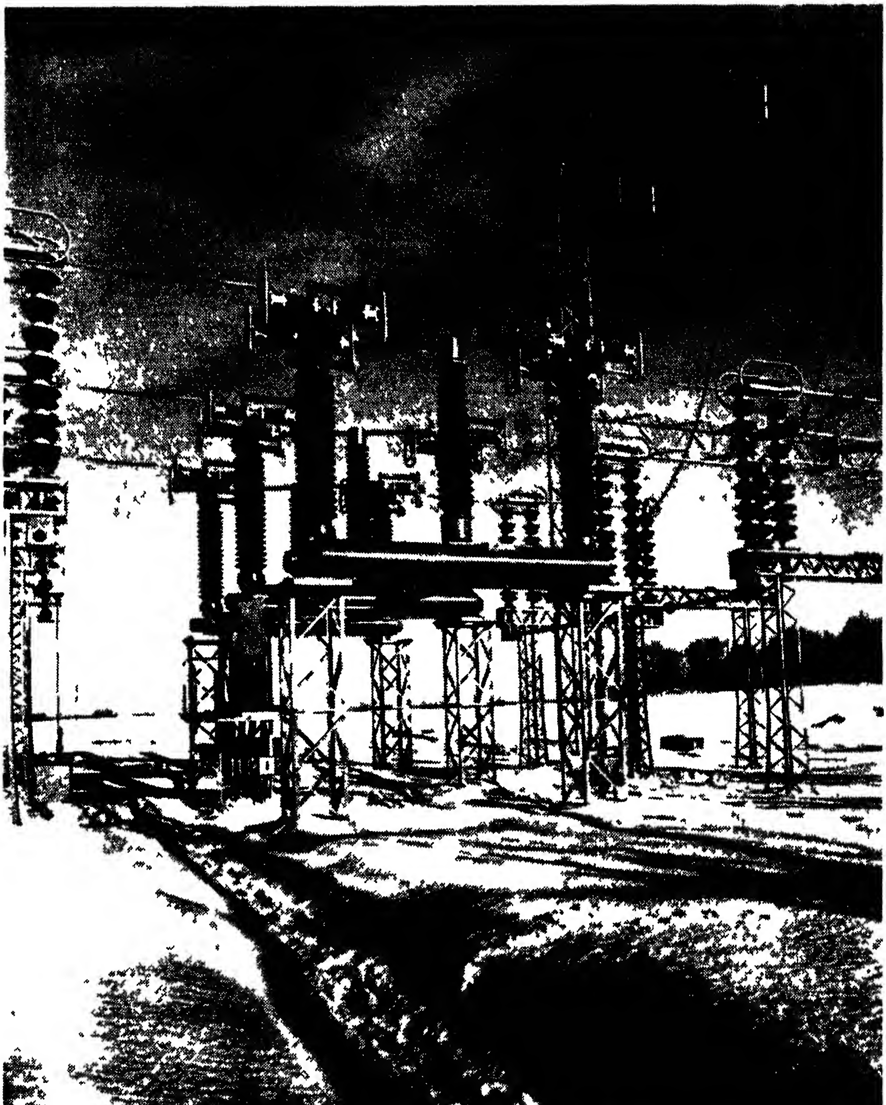


FIG. 18-61.—300 *kV outdoor substation in Montreal, Canada.* (*Associated Electrical Industries Ltd.*).

FIG. 18-62.—165 *kV outdoor substation erected on the roof of the Vila Nova Hydro-Electric Power Station, Portugal. (English Electric Co. Ltd.).*

FIG. 18-63 —220 *kV outdoor substation in Australia (State Electricity Commission, Victoria)*

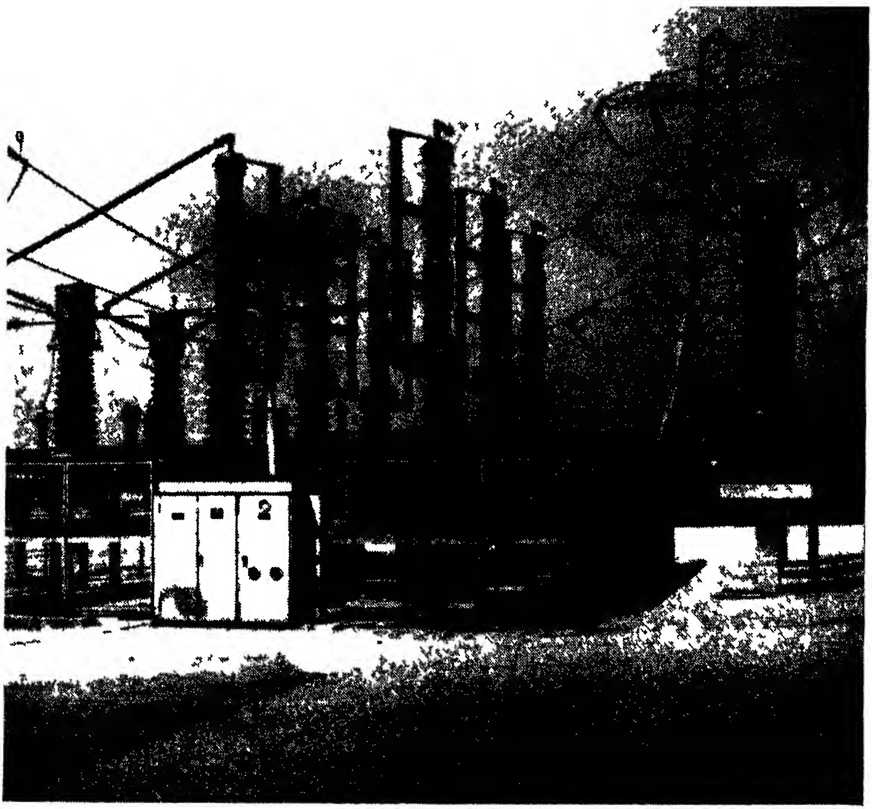


FIG 18-64—*Part of 275 kV outdoor substation at Rochdale, C E G B Merseyside and North Wales Division (The English Electric Co Ltd)*

FIG. 18-65 —*Illustrating the use of a specially designed portable sectional scaling ladder on a 275 kV air-blast circuit-breaker. (The English Electric Co Ltd.)*

"High-level" stations resort largely to steel structures and, apart from the circuit-breaker, the isolating switches, busbars, etc. are all mounted high above ground. In general the design results in a smaller area being required for a given substation, and excellent example being that shown in Fig. 18-62, where the substation is erected on the roof of a hydro-electric power station, and employing air-blast circuit-breakers.

Finally, we may note two examples of outdoor substations, one at 220 kV employing oil circuit-breakers, the other at 275 kV having air-blast circuit-breakers, both floor mounted.

These examples, Figs. 18-63 and 18-64, respectively, are typical and it is of passing interest to note that at 275 kV, the topmost point of the circuit-breaker is approximately 24 feet above ground. In the event of access being necessary to this, or indeed any lower, point, some form of scaling ladder is essential and an example of such a ladder is shown in Fig. 18-65.

Author's Note :—

Designs for 400 kV circuit-breakers have been noted on pages 229, 230, 238 and 239. Illustrations of switching stations employing these very new designs were not available in time for inclusion here.

BIBLIOGRAPHY

B.S.162. Electrical Power Switchgear.

Outdoor High-Voltage Switchgear, R. W. Todd and W. H. Thomson (Pitman & Sons Ltd.).

Substation Practice, T. H. Carr, (Chapman & Hall Ltd.).

Switchgear Principles, P. H. G. Crane (Cleaver-Hume Press Ltd.)

"Automatic Circuit Reclosers," G. F. Pierson, A. H. Pollard and N. Care. "Proceedings I.E.E.," Paper No. 1717. S. Dec. 1954. (102 A, p. 749).

"Automatic Circuit Reclosers," A. H. Pollard, "The BEAMA Journal," May, 1957.

"The Application of Auto-Reclosers," G. S. Buckingham, "Journal I.E.E.," August, 1960.

"High-Speed Reclosing on 11 kV Rural Network," S. H. Money, "The M-V. Gazette," December, 1959.

"The Development of Rural Electrification," G. F. Pierson, "Proceedings I.E.E.," Paper No. 3518, April, 1961, (108 A, p.112).

"The Single Tank Outdoor Oil Circuit-Breaker" "A.E.I. Engineering," September/October, 1962.

"275 kV Indoor Substation at Whitson," "Electrical Times," 20th June, 1963.

CHAPTER XIX

OIL CIRCUIT-BREAKER AND OIL SWITCH OPERATING MECHANISMS

CHAPTER XIX

OIL CIRCUIT-BREAKER AND OIL SWITCH OPERATING MECHANISMS

THE design and type of operating mechanism for use with a particular circuit-breaker or oil switch are of considerable importance in that satisfactory performance in both closing and opening is dependent on the mechanism.

Stated briefly, the duties involved are:—

(*a*) To provide a means whereby the closing operation can be achieved as rapidly as possible and without hesitation at all currents from the normal rating up to the highest peak fault-making current. Under this latter condition, a non-hesitant closing stroke is vitally important at the point of travel when the moving contacts approach and touch the fixed contacts.

(*b*) To hold the circuit-breaker or switch closed by toggles or latches after the closing force has been removed and to provide easy release of this holding device immediately it is acted on by any tripping device, thereby allowing the circuit-breaker or switch to open without delay.

The problem of closing (duty (a)) would call for little comment if the only condition to be met was that of closing on to currents no greater than normal load values. In these circumstances the mechanism would need only to be capable of overcoming the inertia of the moving parts (although this may require a relatively high degree of force in very heavy current circuit-breakers), gravitational forces (in vertical-break designs), and the viscosity of the oil.

The electromagnetic forces due to "grip" and loop effect discussed in Chapter VI are not of a magnitude to be of great concern at normal currents but, unfortunately, the latter are not the only ones to be taken into account and, as we have seen in other chapters, it must be possible to close on to an existing short-circuit, a condition involving the high peak currents which can occur in the first half-cycle of short-circuit. The electromagnetic forces may now be considerable and arise as soon as current is established at contact touch or slightly before, and it is at this moment that any hesitation can have results which may be disastrous, such as contact welding, sustained arcing leading to high and dangerous internal gas pressures, or, at the least, severe contact burning.

It is essential therefore that the speed of closing should be such as to take the moving contact system right through to the end of its movement so that it reaches a position in the fixed contacts at which ample contact pressure exists over the main contacting surfaces. The loop forces oppose the closing stroke and often with such effect that some oscillation of the moving contact system in the vicinity of the fixed contacts is not unknown.

Hesitancy is undoubtedly more likely with hand (manual) closing mechanisms because here the physical strength and skill of the operator are dependent factors. For this and other reasons B.S. 116 recommends that manually operated mechanisms should only be used on circuit-breakers when the breaking capacity does not exceed 150 MVA and that special consideration be given to the means of closing when the fault-current (r.m.s. symmetrical) exceeds 22 kA at voltages up to and including 3·3 kV. This means that the closing device for circuit-breakers or switches outside these limits should be designed for electrical, or other power operation and a review of modern switchgear practice shows that many manufacturers follow this recommendation.

There are many forms of power-closing mechanism available, including solenoid, spring-power, spring-assisted, compressed-air, and hydraulic. The choice of device depends on many circumstances, e.g. whether the circuit-breakers are fully remote-controlled, the size of the breakers, i.e. normal current rating, breaking capacity and voltage, whether high-speed auto-reclosure is required and whether, for example, compressed-air is available for other purposes as with air-blast circuit-breakers.

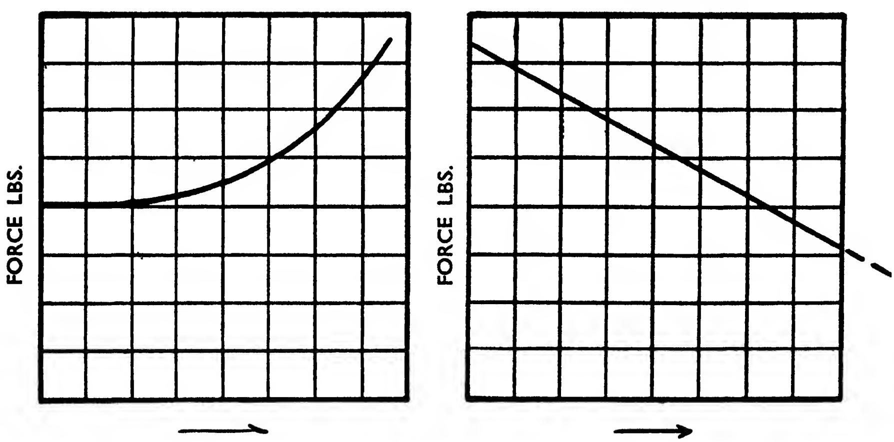
The solenoid type of mechanism is perhaps the oldest and best known of the various forms available and for medium size circuit-breakers is an automatic choice where full remote control is required. Unfortunately, it demands a source of d.c. supply which may be obtained from a battery or a rectifier equipment and both represent costly additions to an installation. Where rectifier equipment is employed, it is preferable that its source of supply be some other than that which is controlled by the circuit-breakers. The d.c. supply to a solenoid is usually at 110 or 240 volts and the design must be such that it will operate satisfactorily at 80% of the normal voltage. The current taken by the solenoid on closing will depend on the size of the circuit-breaker and may be quite high. This in turn will determine the size of the battery or rectifier equipment, and it has to be remembered that on occasion it may be necessary to close several breakers in quick succession causing a heavy drain on a battery when employed. Because the current taken by the closing coil is relatively high, the normal control switch is incapable of dealing with the current direct and therefore a contactor is interposed, the control switch controlling the contactor and the latter completing the heavy current circuit to the solenoid coil. By means of suitable relays, a solenoid-operated circuit-breaker can be readily adapted for auto-reclose operation.

The many installations for primary distribution at voltages up to 11 kV (and to some lesser extent 15/22 kV) in which remote control is unnecessary, have led to the very considerable use of the much cheaper form of closing device where the energy which can be stored in compressed springs is put to use. Present-day designs of such mechanisms include those where the springs are "charged", either manually or by a motor, in readiness for a closing operation, the springs being latched in this state. This latching mechanism may then be released by manual (local) means such as a lanyard or push-button, or electrically (remote) by suitable coil and thus allowing the springs to "discharge" to close the circuit-breaker or switch. In another form which is now extremely popular, the mechanism has a closing handle as in a hand-closing mechanism plus a spring or springs. When the operator

requires to close a breaker or switch with this mechanism, the handle is used in a manner similar to hand-closing but during the initial part of the movement, the springs are being compressed until, at a predetermined point of the movement, the energy stored in the springs is released (automatically) to complete the closing operation of the breaker or switch independent of any further action by the operator, i.e. the final closing operation is taken out of his hands.

This latter type is known generally as a spring-operated manual-closing mechanism, whereas the type first described is known as a spring-operated power mechanism.

At this point it is of interest to note that in a solenoid-operated closing mechanism, the closing characteristic is such as to give maximum force at the end of the stroke, i.e. as the moving contacts reach the "touch" and "closed" position and when the opposing forces are maximum. In spring-operated mechanisms, the reverse is true, in that maximum force occurs at the beginning of the stroke and decreases as the stroke proceeds. This means that in order to ensure ample force as the contacts close, a very powerful spring or set of springs may have to be employed. The closing characteristics of the two mechanisms are illustrated graphically in Fig. 19-1.



(A) PLUNGER STROKE
(*Solenoid*)

(B) SPRING STROKE
(*Spring close*)

FIG. 19-1.—*Closing characteristics of solenoid and springs.*

On the problem of tripping the mechanism (duty (b)) it is clearly essential that, on the occurrence of a fault, (e.g. overload, earth-fault or short-circuit) the circuit-breaker should open with certainty and as quickly as possible after the tripping impulse has been received. This impulse may come from direct-acting protective coils associated with the mechanism, e.g. series or current transformer operated overload coils, or from a relay associated with a particular system of protective gear (see Chapter XV), the relay in turn energising a shunt trip coil at the mechanism. The efficient functioning of the mechanism on tripping depends very largely on the mechanical design, the

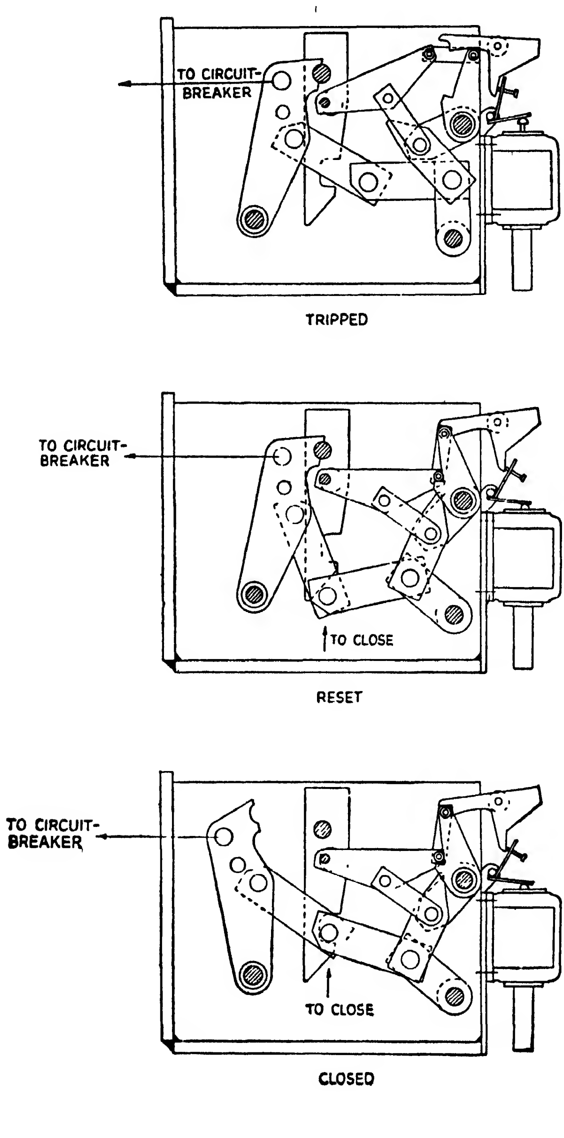


FIG. 19-2.—*Link diagram of closing mechanism suitable for hand, solenoid or spring-operation (Johnson & Phillips Ltd.).*

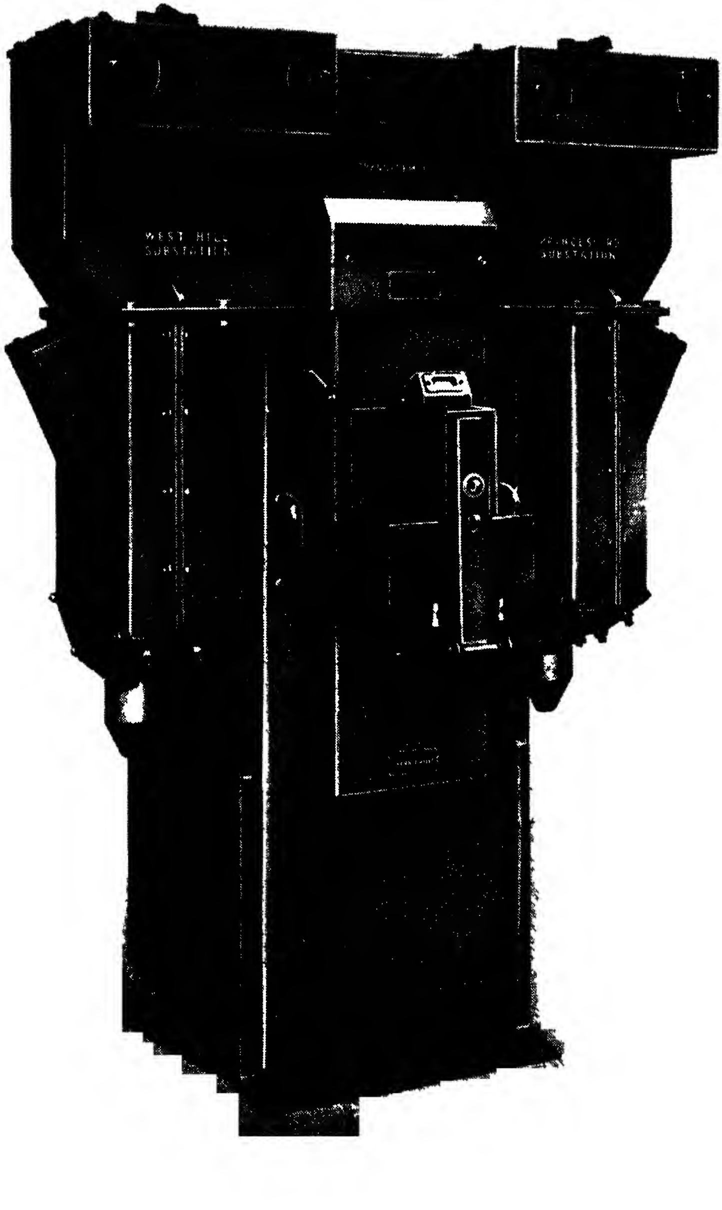


FIG. 19-3.—*Typical hand-operating mechanism on the circuit-breaker forming part of a ring main unit (Johnson & Phillips Ltd)*

inertia of the parts which have to be moved from rest to cause an opening operation being kept as small as possible. The number of toggle joints employed should be kept to a minimum as, if these are excessive, the time taken to break them on tripping is increased.

When a "train" of toggles is broken to trip a breaker or switch, the toggles must be reset before another closing operation can be performed. In hand-operated mechanisms, resetting usually takes place as the handle is lifted to its "ready-to-close" position. In power-operated mechanisms, resetting is automatic after the opening movement is complete. A typical link diagram is given in Fig. 19-2 showing the links as they appear in the "tripped", "reset" and "closed" positions.

Most hand-operated mechanisms are designed to be "trip-free" which means that at all stages during a closing operation the circuit-breaker is free to trip open should a tripping impulse be given. A reverse trip is often provided which may take the form of a rack and pawl and, as the latter passes over the teeth of the former during the closing stroke, a spring is compressed. Should the operator hesitate, due to the forces opposing him, or because of contact pressure, and then reverse the handle rotation by a few

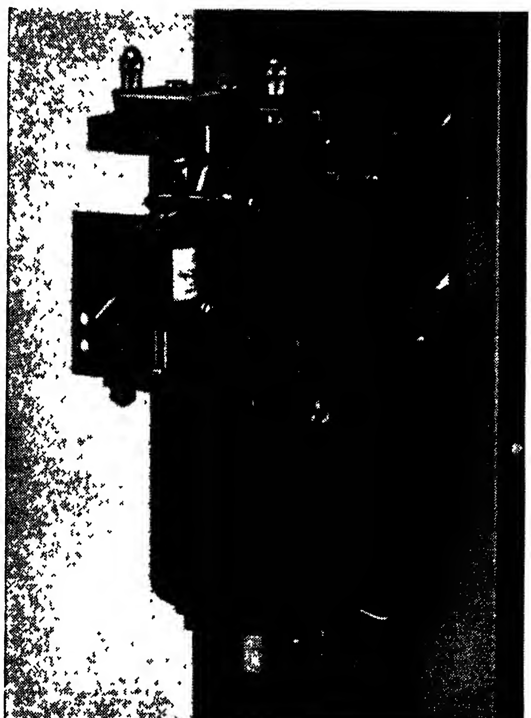


FIG. 19-5.—*Solenoid-operated closing mechanism. Cover removed (Johnson & Phillips Ltd.).*

degrees, one of the teeth catches on the pawl to rotate the reverse trip unit to the point where it lifts the trip bridge and trips open the circuit-breaker. A device of this type is used on some of the designs to be shown later and, in a spring-operated power mechanism, it is also used to prevent slow opening of the circuit-breaker, a condition which might arise if for some reason, such as badly burnt contacts, the full travel of the closing stroke has not been made and one of the final toggles has not gone sufficiently over centre.

Fig. 19-3 shows a hand-operating mechanism employed on a circuit-breaker unit, while Fig. 19-4 shows the mechanism in cross-section in its three positions.

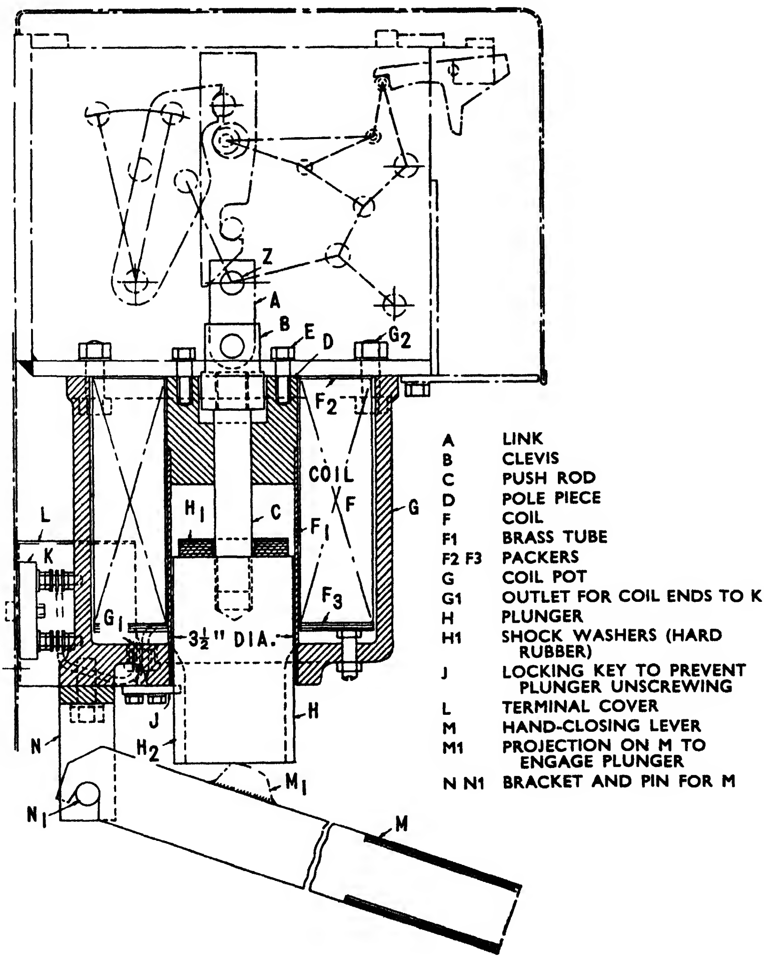


FIG. 19-6.—*Cross-section of typical solenoid-operated mechanism (Johnson & Phillips Ltd.).*

A solenoid-operated closing mechanism is illustrated in Fig. 19-5 and in cross-section in Fig. 19-6. In this latter illustration, the link mechanism above the solenoid coil is that previously shown in Fig. 19-2, the mechanism being "reset" and the plunger down ready for a "close" operation.

A spring-operated power mechanism using the same linkage is that shown in Fig. 19-7, a design which employs four springs placed at the corners of

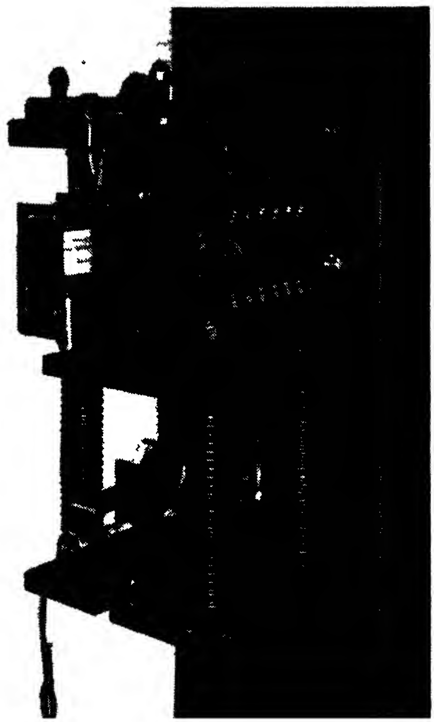


FIG. 19-7.—*Closing mechanism for spring operation. Covers removed (Johnson & Phillips Ltd.).*

the upper and lower compression plates. In other designs, six springs are used, while in others single or concentric springs may be employed. Various precautions must be taken with devices of this type and in that shown, the following are included:—

(*a*) The springs, if charged, cannot be released while the circuit-breaker is closed.

(*b*) Interlocks prevent slow-closing or slow-opening of the circuit-breaker in its service position.

(*c*) If the springs fail, it is possible to hand-close the circuit-breaker.

Features of the device are that the springs can be recharged while the circuit-breaker is closed, thus preparing in advance for the next closing operation. Release of the springs can be by an electrically operated coil

for remote control, by hand through the medium of a lanyard or, if in the case of a supply failure to a release coil, by an emergency hand release.

We have noted earlier (Fig. 19-1) how the spring-operated power mechanism has a falling force/distance characteristic. The employment of a suitable toggle arrangement in the design illustrated helps to overcome this drawback, the arrangement being such that the closing links are made to approach a near-centre position at the end of the spring travel. This arrangement also gives the operator some mechanical advantage when charging the springs. These features are demonstrated in Fig. 19-8 at (a) and (b).

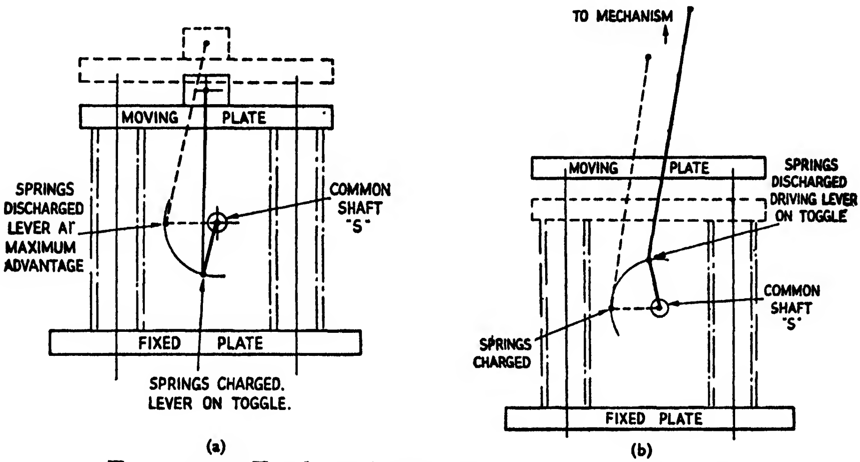


FIG. 19-8.—*Toggle mechanism used in spring-closing device (Johnson & Phillips Ltd.).*

Having designed a spring-closing mechanism which will satisfactorily close a circuit-breaker on to an existing fault where the opposing forces are a maximum, it may be found that when the same mechanism closes against much reduced opposition, e.g. closing on normal load, very high speeds are attained which cause considerable stressing in parts of the mechanism. Some form of buffering is therefore desirable to take up this surplus energy and a simple arrangement is that which employs pads of rubber above the upper compression plate (the moving plate in Fig. 19-8). In other designs an oil dashpot is used which is effective at high switching speeds but is less so at speeds damped down by the opposing forces when switching on to faults.

Spring-closing devices of the power type are employed on breakers of various sizes. That shown in Fig. 19-7 is for breakers up to 350 MVA at 11 kV and is such that charging the springs can be readily carried out by means of a hand lever. For larger breakers, the spring-closing device may require very considerable effort in the process of charging the springs, and in this case it is usual to arrange that this function is performed by an electric motor.

Fig. 19-9 shows another form of spring-operated power mechanism using much lighter springs and only two of them, disposed one on each side of the link mechanism.

FIG. 19-9.—*Light spring-operated power mechanism. Cover removed, spring-charged, breaker open* (*Johnson & Phillips Ltd.*).

FIG. 19-10.—*Inserting handle to charge springs. Handle is lifted in slots and cannot be removed until springs are latched in charged position (Johnson & Phillips Ltd.).*

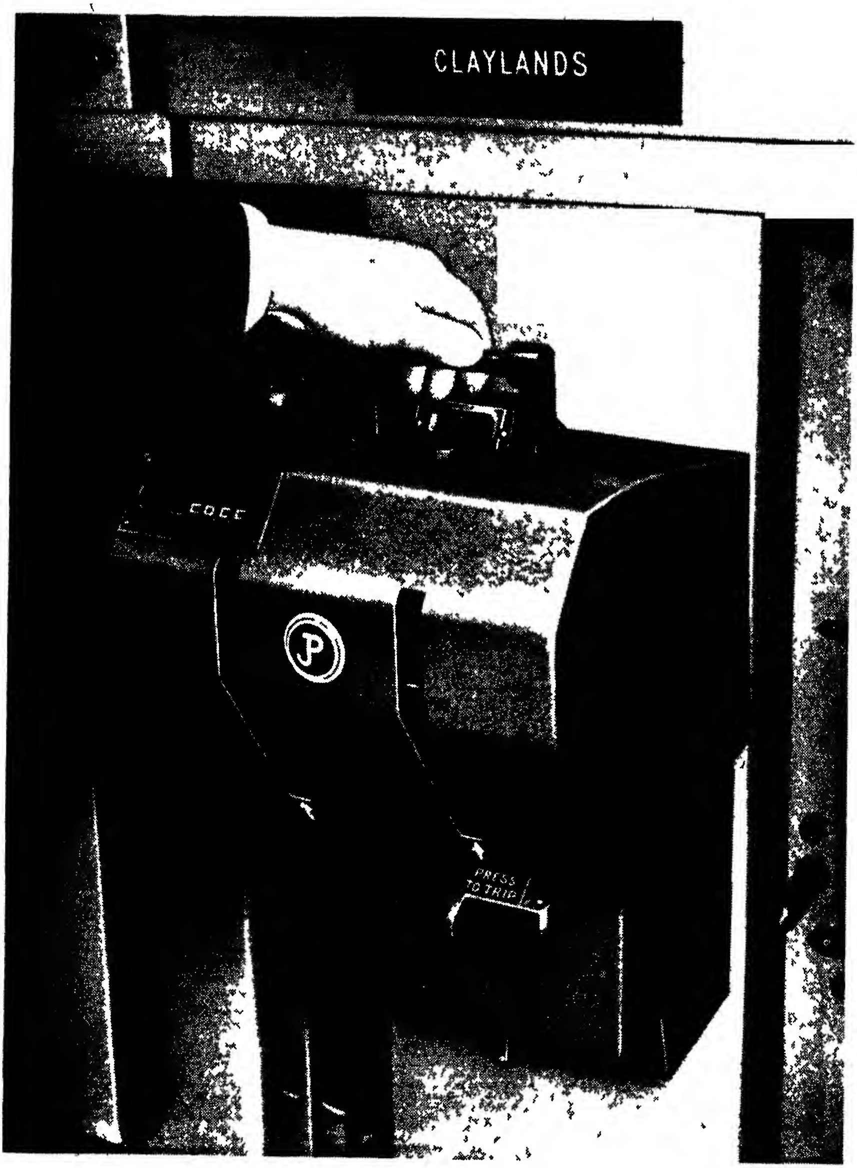


FIG. 19-11.—*Spring release handle to close circuit-breaker (Johnson & Phillips Ltd.).*

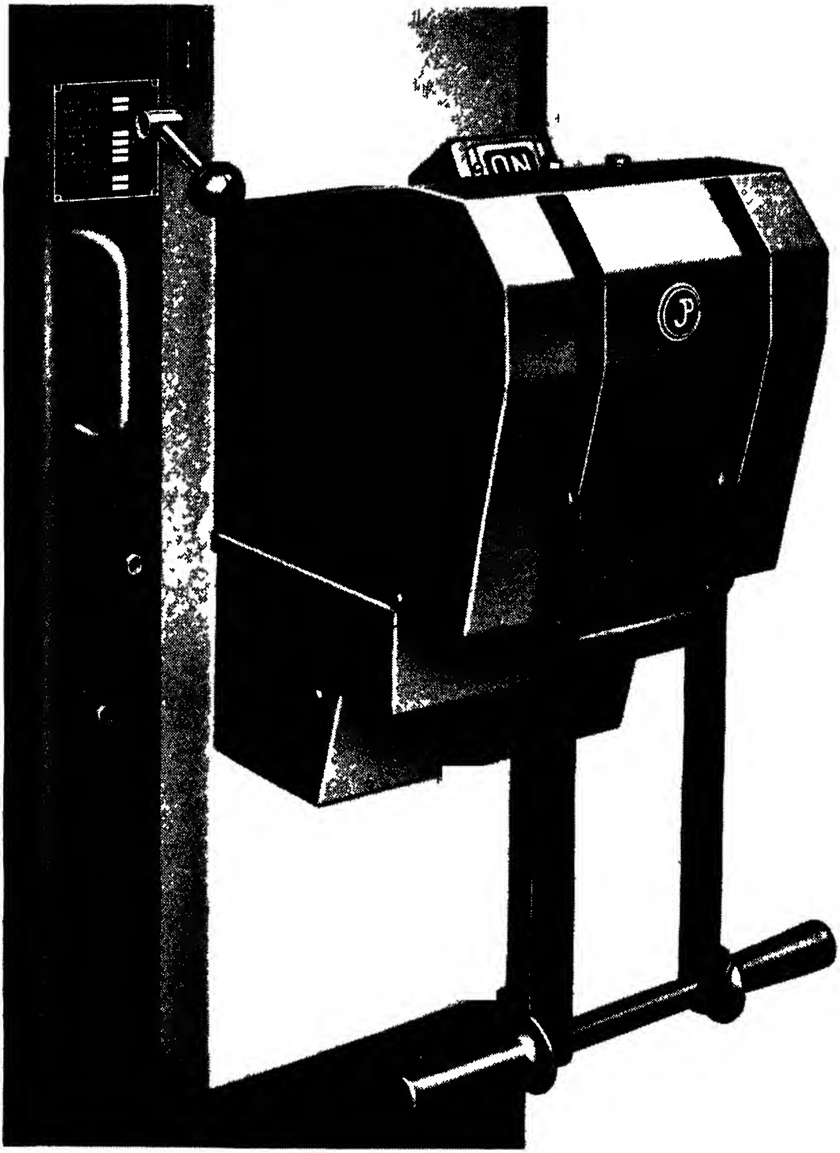


FIG. 19-13.—*Operating mechanism as Fig. 19-12 with handle in breaker closed position (Johnson & Phillips Ltd.).*

FIG. 19-14.—*Showing articulated design of operating handle (Johnson & Phillips Ltd.).*

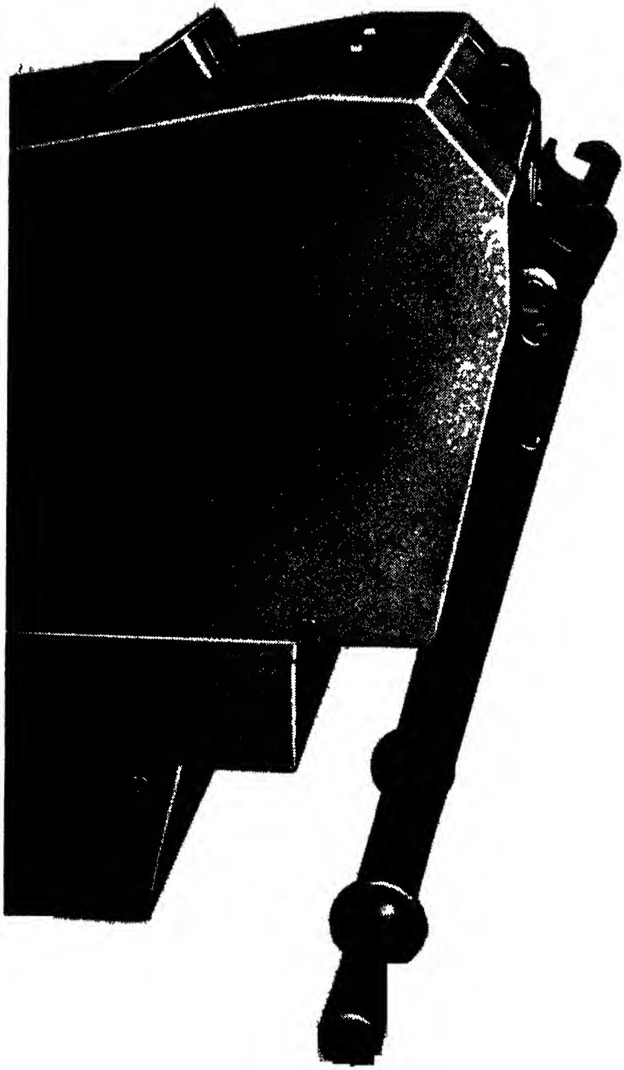


FIG. 19-15 —*Position of handle taken up when disengaged from the drive* (*Johnson & Phillips Ltd*)

Figs. 19-10 and 19-11 show (respectively) the operations of spring charging and releasing to close the circuit-breaker, the latter being a hand-operated function by pulling the handle above the mechanism forward. The various precautions noted earlier apply equally to this mechanism, which also includes a reverse trip device generally as that shown in Fig. 19-4.

The other form of spring-closing device is that where the energy stored in compressed springs is produced by the movement of a handle during the initial part of the operation and is released to complete the closing operation at a predetermined point in the stroke and independently of the operator. A design of this type is noted in Fig. 19-12 which shows the three stages, closed, tripped, and reset.

In this mechanism, resetting is effected by raising the handle to its upper limit, as shown in Fig. 19-12. This handle movement not only resets the internal driving links and tripping toggles but it also engages the *forward* ends of the springs under suitable retaining catches.

From this position, downward movement of the handle compresses the springs from the back ends through a system of links and levers. As the springs compress and stored energy builds up, the handle links take up a toggle formation to the advantage of the operator and, as the links pass over dead centre, they push the spring retaining catches free, thus releasing the *forward* ends of the springs which discharge to close the circuit-breaker through the driving links while the operator takes the handle through to the vertical (downward) position free of the circuit-breaker. The final handle position and a general external view of the complete mechanism is noted in Fig. 19-13.

To trip the circuit-breaker, the handle is lifted, this reverse upward motion causing tripping through a ratchet and pawl device as previously described in relation to Fig. 19-4. With the circuit-breaker in the open position, no stored energy remains in the springs.

In the design illustrated, a facility is provided whereby should an operator find, after commencing a closing operation, that he is not required to close that particular breaker, he can disengage the positive drive by depressing two catches on the articulated handle, as shown in Fig. 19-14, and allow the handle to drop down to the position shown in Fig. 19-15.

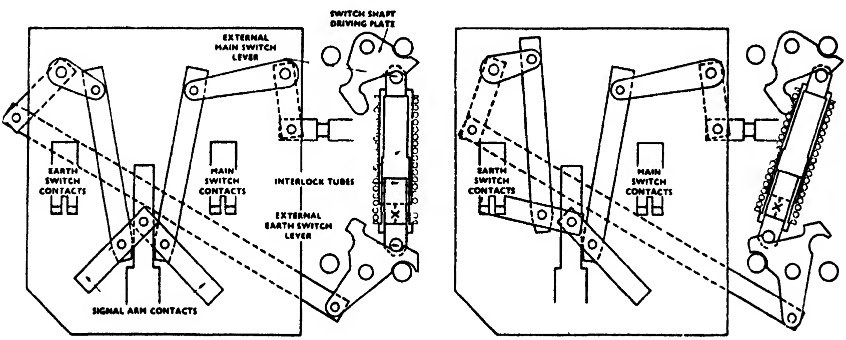
From the position shown in Fig. 19-15, the catches will re-engage as soon as the handle is lifted.

Another facility which must be provided in spring-operated, manually-closed mechanisms is that it shall be possible to close a circuit-breaker slowly for inspection, maintenance and/or adjustment. This means that some method must be devised whereby the mechanism is converted to manual-closing throughout, i.e. the springs take no part in the operation. Coupled with this it is essential to ensure that slow closing can only be performed when the circuit-breaker has been completely isolated from its service or earth positions. (See Addendum to B.E.B.S.—S 2 (1955).)

To achieve all this in the design described and related to a switchgear unit of the vertical isolation type as described in Chapter X, the circuit-breaker is first isolated and then withdrawn, on its carriage, from the fixed housing. In this position, a slide bolt is ejected from the carriage structure which makes it possible to withdraw a link attached to the spring retaining catches at the rear of the carriage. Movement of the operating

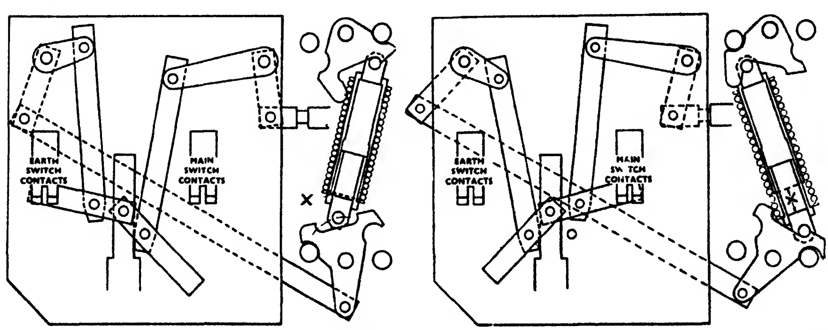
handle will not now charge the springs but the rigidity of the latter in their discharged state is sufficient to operate the closing mechanism at hand-closing speeds. The bolt and the links must, of course, be restored to normal before the circuit-breaker carriage can be returned to the housing.

In Chapter VI we have noted the increasing use of load-breaking, fault-making oil switches and have illustrated various designs. Because of the facility such switches must have to make on to an existing short-circuit, the closing mechanism adopted is generally of the manual spring-operated type we are now considering. As we have seen, the oil switch incorporates switch blades for the primary circuit and for earthing, and in one design separate switch blades are employed, operated by individual driving shafts and linkages but from a common spring mechanism. How this is achieved is seen from Fig. 19-16, which, with the accompanying notes, is self-explanatory.



SWITCH WITH BOTH EARTH AND MAIN SWITCH BLADES OPEN. NOTE THE SPACE "X" BETWEEN THE TWO PARTS OF THE SPRING'S CORE. THIS ALLOWS EITHER EARTH OR MAIN SWITCH TO BE CLOSED ONTO ITS CONTACTS BUT WILL NOT PERMIT BOTH TO BE CLOSED AT THE SAME TIME.

EARTH SWITCH CLOSED. NOTE THE SPACE "X" BETWEEN THE TWO PARTS OF THE SPRING'S CORE.



WITH EARTH SWITCH CLOSED, AN ATTEMPT HAS BEEN MADE TO CLOSE THE MAIN SWITCH. THE CORE ENDS HAVE BUTTED TOGETHER AND SPACE "X" HAS DISAPPEARED THUS PREVENTING FURTHER MOVEMENT OF THE MAIN SWITCH.

MAIN SWITCH CLOSED. NOTE THE SPACE "X" BETWEEN THE TWO PARTS OF THE SPRING'S CORE.

FIG. 19-16.—*Manual spring-operated closing mechanism as applied to an oil switch with earthing facilities (Johnson & Phillips Ltd.).*

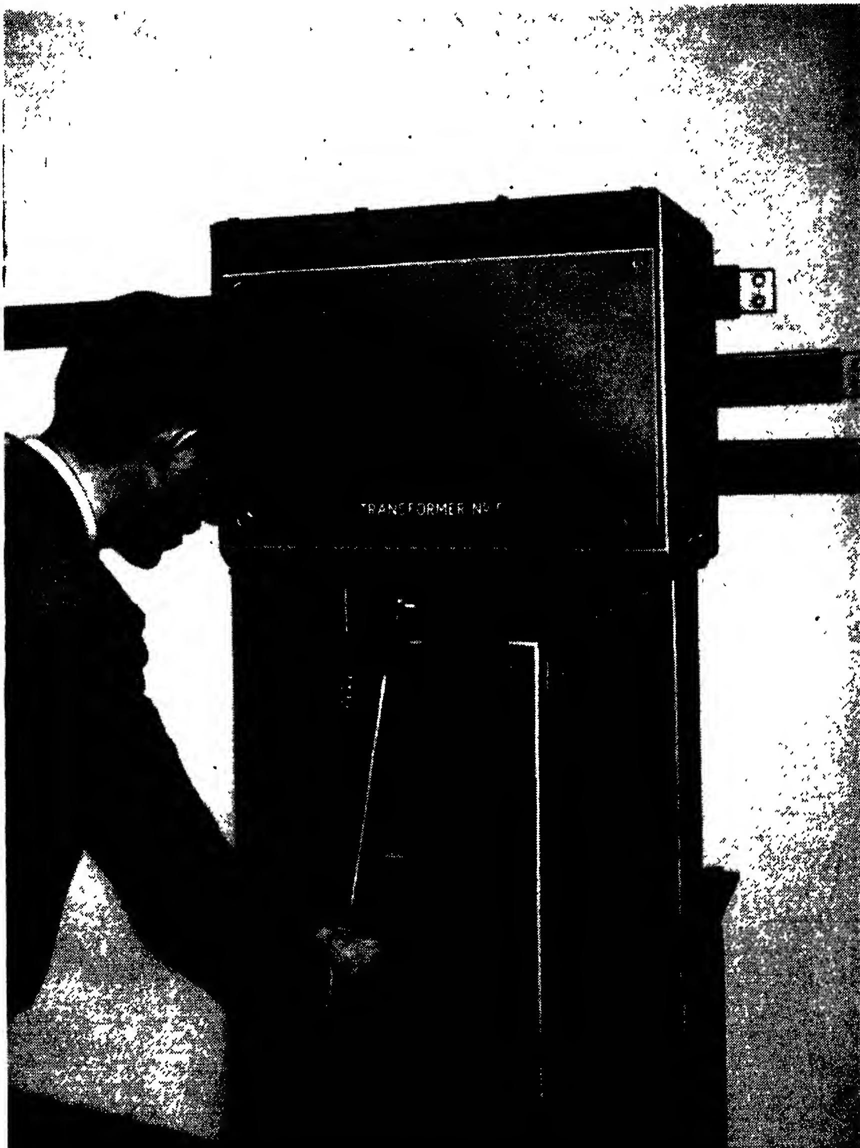


Fig. 19-17.—*Operating handle in "closed" position on main switch (Johnson & Phillips Ltd.).*

In Fig. 19-17, an operator is seen with the operating handle in position having closed the main switch on the upper spigot and lever pin. To close the earth switch the same handle is used but in this case is placed over the lower spigot and lever pin and the handle lifted vertically.

The lever pin in this design, having passed over centre, is driven by the spring to pick up the switch shaft driving plate and rotate it to close the switch at speed and independent of the operator. To open either switch, the reverse procedure is applied and again the spring takes over from the operator to provide a quick-break opening. An interesting feature of this mechanism is the single spring with an internal core of tubes, having a limited movement as between tubes (marked 'X' in Fig. 19-16) to provide a foolproof interlock.

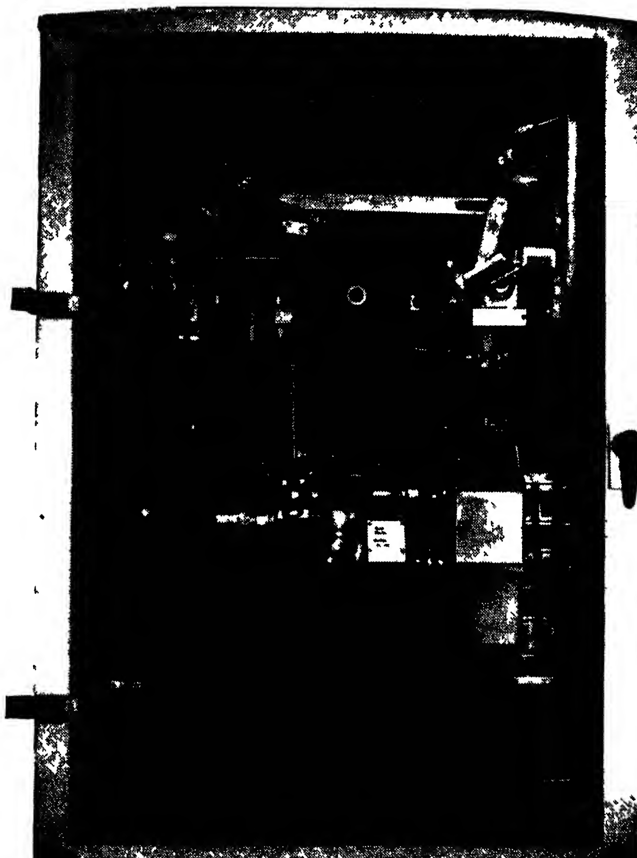


FIG. 19-18.—*Compressed-air operating mechanism with unit compressor, applied to 66 kV outdoor oil circuit-breaker (The General Electric Co. Ltd.).*

Two examples of compressed-air closing mechanisms are illustrated in Figs. 19-18 and 19-19, both employed on large outdoor oil circuit-breakers.

That shown in Fig. 19-18 is one where a unit compressor is used at each circuit-breaker, the compressor being seen at the bottom of the cabinet, the latter carried on the circuit-breaker floor mounting framework, In this arrangement, an air cylinder and piston in the upper part of the cabinet drives the link mechanism to close the circuit-breaker, the air supply being controlled by electro-pneumatic valves so that remote operation can be provided.

In the arrangement shown in Fig. 19-19, each mechanism has its own air receiver which will be fed from a storage point and central compressor plant, very similar to the arrangements we have noted in Chapter VIII when considering air-blast circuit-breakers. The receiver can provide for two closures without make-up air.

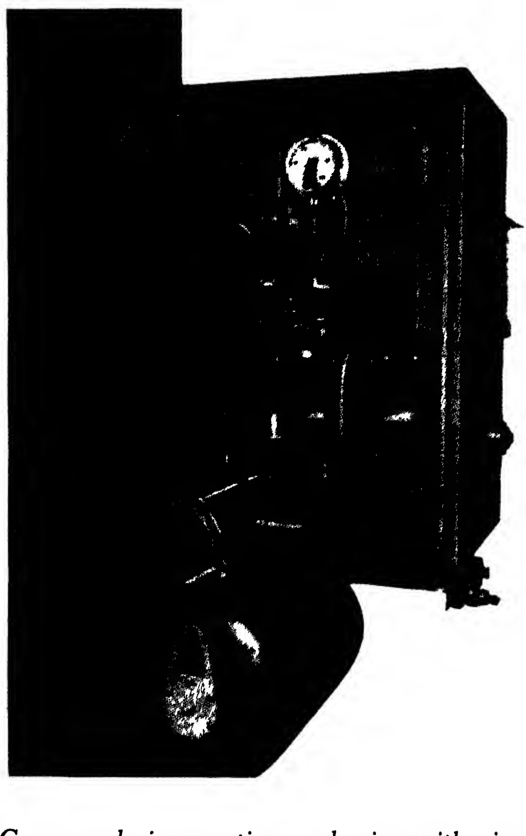


FIG. 19-19.—*Compressed-air operating mechanism with air receiver, applied to a 132 kV outdoor oil circuit-breaker (Associated Electrical Industries Ltd.).*

Air will be admitted to the closing piston by means of electrically operated valves and suitable interlocks ensure that a closing operation, once initiated, must be completed, thus ensuring that the circuit-breaker will then open at its normal speed because the opening springs must be fully compressed before the circuit-breaker can trip.

In another design of outdoor oil circuit-breaker (33 kV 750 MVA) a spring-closing mechanism is charged by a motor-driven hydraulic pump. This mechanism, with its pump, is shown in Fig. 19-20.

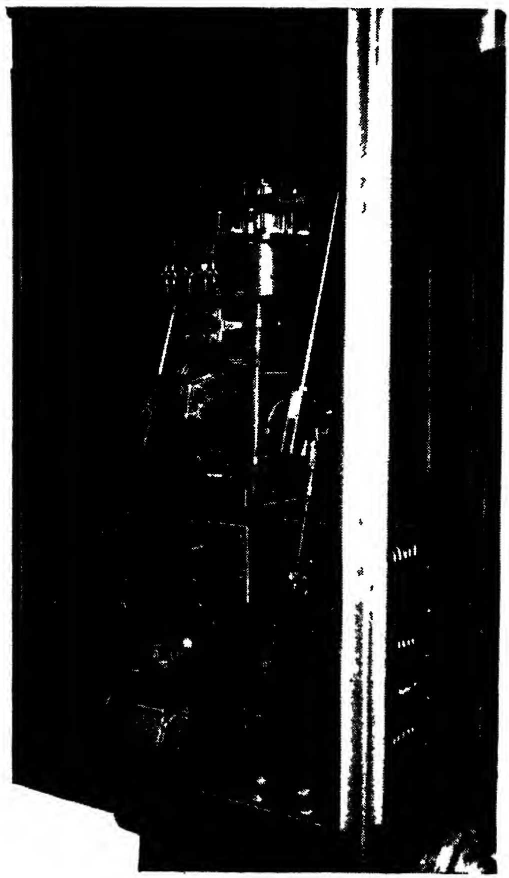


FIG. 19-20.—*Spring-closing mechanism for 33 kV outdoor oil circuit-breaker, with motor-driven hydraulic pump for charging the spring (A. Reyrolle & Co. Ltd.).*

The latching of the closing spring is assisted by the inherent pressure in the charging cylinder acting on the latch until it reaches its final position. The pump motor control is so arranged that when the closing spring is discharged, the charging cycle is automatically re-commenced. In this design, the closing spring is a chrome-vanadium torsion bar anchored to both the mechanism and the main frame of the circuit-breaker and when charged is locked in position by a roller latch. The closing operation is initiated by a remotely-controlled spring release coil with provision for local manual release.

The tripping mechanism is powered by a similar but lighter torsion-bar spring which is charged by the discharging action of the closing spring so that the mechanism is prepared to accept any tripping impulse which may be transmitted to it either manually or from the associated protective gear.

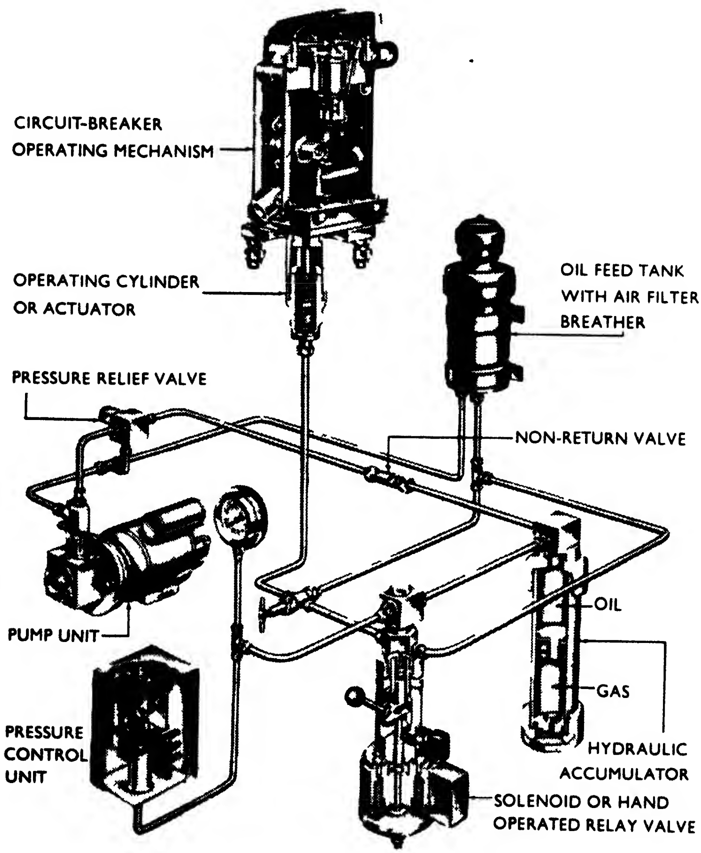


FIG. 19-21.—*Pneumo-hydraulic closing mechanism (Brush Electrical Engineering Co. Ltd.).*

Another interesting closing mechanism applied to a 33 kV outdoor circuit-breaker is a stored energy device the basic element of which is a hydraulic accumulator. This scheme shown in Fig. 19-21, is one in which oil is stored at high-pressure and is released by a relay valve to an operating cylinder to close the circuit-breaker. The valve solenoid draws its supply from a 30-volt, 15 ampere-hour tripping battery.

Referring to Fig. 19-21, the accumulator is pre-charged with gas to a pressure of 2 000 lbs. per sq. in. Oil is pumped into the other end of the cylinder and the separating piston compresses the gas to 4 000 lbs. per sq. in. at which pressure the stored energy is sufficient for a number of successive closing operations without re-pumping the oil. As the pressure on both sides of the piston is equal, the piston seals are not subjected to differential pressures.

In the normal valve position, oil is contained under pressure in the accumulator, in the pipe line to the non-return valve, and in the pipe line up to the main valve crating. When the valve solenoid is energised, the operating cylinder is initially sealed from the oil feed tank. Pressure is then applied to the operating cylinder through a restricted orifice in order to take up any slack in the mechanism and the final movement of the valve spindle lifts the main valve to allow full flow of oil to the operating cylinder. An electrically-driven pump supplies oil from the reservoir to the accumulator, the motor being under the automatic control of a pressure switch, starting up when pressure falls below a set value and stopping the motor when the required pressure is restored.

A lock-out pressure switch interrupts the relay valve solenoid circuit if the accumulator pressure is too low for a satisfactory closing operation and a further pressure switch operates a warning light at the remote control panel when pressure is low.

For emergency operation, the relay valve can be operated by hand to close at normal speed. Hand charging of the accumulator is possible via an attachment fitted to the pump shaft.

It is claimed for this method of operation that the substantially constant pressure on the piston of the operating cylinder gives good closing characteristics, that the light mass of moving parts results in low impact forces on the mechanism and it eliminates heavy springs or heavily loaded catches. Gas is not in direct contact with the fluid and as the latter is in a closed circuit it is not consumed.

CHAPTER XX

NEUTRAL POINT EARTHING

CHAPTER XX

NEUTRAL POINT EARTHING

THE majority of three phase systems today operate with an earthed neutral, earthing being achieved either directly or through an impedance. Nevertheless, there are quite a number of systems operating with a free neutral, i.e. insulated systems, and the advocates of this method claim its superiority on the grounds that the supply can be maintained for a time on the two healthy lines while an earth-fault exists on the third. This argument is particularly true for an overhead transmission system when the failure of one line to earth is not so likely to develop into a fault between two or more lines. Later in this chapter details will be noted of a protective system applied to insulated systems. On a cable system, however, one line down to earth leads to heating and burning with the likelihood that, within a short time, an earth-fault will develop into a phase-fault and to avoid this possibility, quick acting earth fault protection is required.

The advantages of the earthed neutral are many and include:—

(a) Persistent arcing grounds are eliminated if suitable protective gear is employed.

(b) Earth-faults comprise a short-circuit between the faulty line (or lines) and earth and can be utilised to operate protective relays to disconnect the fault.

(c) The voltage on healthy lines is held to line/neutral voltage.

(d) Induced static charges are conducted to earth without disturbance.

It is of interest here to note that B.S.116 : 1952 (oil circuit-breakers for a.c. systems) recognises various conditions of system earthing in relation to circuit-breaker design (insulation co-ordination). They are:—

(a) The condition where at least one of the neutral points of a three phase system is permanently earthed either solidly or through a resistor or reactor of low impedance. Such a system is considered to be effectively earthed if, during line to earth faults, the voltage to earth of the sound lines does not exceed 80 per cent of the voltage between lines of the system. In general, this is only achieved when *all* transformer neutrals are solidly earthed.

(b) The condition where at least one of the neutral points of a three phase system is earthed normally through an arc suppression coil. On such a system it is the intention that the majority of line to earth faults will be self-clearing without interruption to the supply. Where such faults are not self-clearing, three methods of system operation are recognised:

(i) Where the fault is automatically disconnected after a short delay (see page 703 and Fig. 20-4).

(ii) Where non-automatic disconnection is used the faults are generally cleared quickly although they may be allowed to persist for several hours provided the total duration does not exceed 125 hours per annum with a maximum of 8 hours in any 24.

(iii) Where the faults are allowed to remain for a longer duration than in (ii) but not approaching continuous operation with one line earthed.

(c) All neutral points of a three phase system are insulated from earth.

(d) A single phase system with one line earthed.

Standard circuit-breakers (particularly those for outdoor service) complying with B.S.116, are those for use on systems earthed as in (a), (b)(i), (b)(ii) and (d). Where the earthing conditions are as noted in (b)(iii) and (c), special consideration has to be given to the circuit-breaker and other insulation levels and for guidance in this respect, a study should be made of Appendix D, Section 2a in B.S.116 coupled with clauses 20, 41 and 42. These latter also give details of the impulse voltage test values to be applied on outdoor circuit-breakers for service voltages of 22 kV and above, for effectively and non-effectively earthed systems.

Regulations issued by the Electricity Commissioners prohibit multiple earthing except in special circumstances and then only with the consent of the Postmaster-General. This is due to the possibility of interference with communication circuits owing to the circulation of current between neutrals. Whether or not such interference is possible may be controversial and those in favour of multiple earthing point out that its advantage is that it practically eliminates the danger of losing the earthed neutral, a danger which is always present when only one machine or transformer out of a bank is earthed and, for one reason or another, may be disconnected from the system.

Single point earthing, on the other hand, also has its advantages. It permits earth-fault currents to be limited by the insertion of a single impedance in the earth connection. It maintains, thereby, constant impedance value in the earth connection irrespective of the number of connected machines or transformers, or, when no external impedance is employed, limits the value of earth current to that which can be fed from one machine or transformer.

Solid earthing is normal practice in Great Britain for systems in excess of 33 kV and is, in general, the method adopted on low-voltage systems. At the higher voltages, however, it can result in very heavy currents flowing to earth, values being comparable in magnitude with those for interphase faults. Because on overhead systems the majority of faults are earth-faults, heavy currents may be a severe shock to the system if faults are frequent and, therefore, there is an argument for the introduction of some form of limiting resistance to reduce the fault current to a value necessary only for the operation of the protective gear.

On medium-voltage systems, e.g. 400 volts, external resistance is unnecessary. Here, the voltage available to cause the flow of earth-fault current is only 230 volts, and the fact that the earth resistance at the earth plate may be as high as 1 ohm (in some cases more) indicates that the earth-fault current will be of the order of 230 amperes. If higher values than 1 ohm arise, it is clear that restriction of earth current arises, sufficient, maybe, to make operation of protective gear difficult.

For systems between the limits of voltage noted above, the use of current limiting devices in the neutral connection to earth is the rule. In British practice a resistor, either of the grid or liquid type, is favoured. On the Continent, reactance earthing is often used, the advantage claimed being that for corresponding ohmic values, the reactor is of smaller bulk than the resistor. No standard ohmic values for such devices exist but, in general, it is common practice to fix a value which will limit the earth current to the full-load rating of the largest generator or transformer or, alternatively, to about twice the normal current of the largest feeder.

On this basis, it is usual, with commercial current transformers and earth-fault relays, to protect up to 80/85% of the machine or transformer winding, the relay setting being 20/15%. Lower values are possible but stability may be thereby sacrificed due to the possibility of unwanted tripping by spill currents when heavy through faults occur. In any event, earth-faults in the windings at points less than 15 or 20 per cent of the total winding length from the neutral are rare because the potentials above earth at such points are only these percentages of the full line to neutral voltage.

Assuming that it is agreed to limit the fault current to earth to a value equal to the full-load current of the largest machine or transformer, the value of impedance to be inserted in the neutral connection to earth is

$$R=\frac{V}{I}$$

where R=neutral impedance in ohms
V=line/neutral voltage
I=full-load current of largest machine or transformer in amperes.

If a relay setting of 20 per cent is chosen, this then affords protection to 80 per cent of the windings on the largest machine, while a greater percentage of the windings of smaller machines running in parallel will be protected. If, at some later date, a still larger machine is added, it may be necessary to take steps to reduce the ohmic value of impedance in order to get maximum winding protection of the larger machine. To determine the percentage of winding unprotected on any machine, the following expression is used:—

$$\%\text{ of winding unprotected}=\frac{R.I.100}{V}$$

where R=ohmic value of impedance
I=minimum relay operating current
V=line/neutral voltage

and noting that if a 20 per cent relay setting is used then I is 20 per cent of the full-load current of the machine being checked.

The problem of neutral point earthing of transformers may be resolved into two parts—h.v. and l.v. That of h.v. earthing is little different to that of generators, to provide the same degree of protection. That of l.v. has the added and important feature that it reduces somewhat the danger to life in that it prevents any voltage above normal appearing on the l.v. winding, an important matter in domestic and industrial applications.

The importance of a low value of earth resistance in low-voltage systems has already been mentioned. In the 9th Edition of J. & P. Transformer Book, the following expression is given:—

$$Z_N = \frac{V^2}{n \cdot kVA \cdot 1\,000} \text{ ohms}$$

where Z_N = impedance in neutral in ohms

V = line voltage

kVA = rating of transformer

n = neutral short-circuit current in terms of full-load line current.

Taking as an example a 2 000 kVA transformer with an earth-fault relay set at 40 per cent then, with respect to the 400 volt side,

$$Z_N = \frac{400^2}{0{\cdot}4 \cdot 2\,000 \cdot 1\,000} = 0{\cdot}2 \text{ ohms.}$$

This can be checked very simply as follows.

By symmetrical component theory (see Chapter IV) the zero phase sequence impedance is

$$3R + j\,Xo$$

where R = resistance

Xo = zero phase sequence reactance.

Assuming for the moment that Xo is sufficiently small to be ignored, then:—

$$\text{Earth-fault current} = \frac{3E}{3R}$$

where E = line/neutral volts

$$\frac{3 \cdot 231}{3 \cdot 0{\cdot}2} = 1\,155 \text{ amps.}$$

The full-load current of the 2 000 kVA transformer at 400 volts is 2 890 amps and with a relay setting of 40 per cent, the operating current is $40/100 \cdot 2\,890 = 1\,155$ amps.

It can be shown that when there are a number of machines operating in parallel, the value of earth-fault current varies with the number of machines operating at any one time.

This can be demonstrated by symmetrical component theory (see Chapter IV). Here we have:—

Z_1 = positive phase sequence impedance

Z_2 = negative phase sequence impedance

Z_0 = zero phase sequence impedance.

For the purpose of demonstration assume that there are six alternators all equal in output and characteristics, and that arrangements exist whereby only one machine may be earthed at a time. The impedances of each machine may well be:—

$$Z_1 = 20 \text{ per cent}$$
$$Z_2 = 14 \cdot 6 \text{ per cent}$$
$$Z_0 = 6 \cdot 4 \text{ per cent.}$$

Taking the case first where only one machine is operating, and assuming zero resistance in the neutral connection, then:—

$$\text{Fault current} = \frac{3E}{Z_1 + Z_2 + Z_0}$$
$$= \frac{3E}{0 \cdot 2 + 0 \cdot 146 + 0 \cdot 064} = 7 \cdot 32E$$

Now let us assume that all six machines are operating in parallel but that only one is earthed, then:—

$$\text{Fault current} = \frac{3E}{\left(\frac{0 \cdot 2}{6}\right) + \left(\frac{0 \cdot 146}{6}\right) + 0 \cdot 064} = 24 \cdot 4E$$

so that in the latter case the fault current is more than 3 times that of the first case i.e. in the ratio 24·4 : 7·32.

It will be noted that in the foregoing, zero resistance has been assumed in the neutral connection. If there is resistance at this point, it may be that its value is so high in relation to the reactance that it is the resistance which determines the value of fault current. For example, assume we have two 2 000 kVA transformers which may operate singly or in parallel and that the resistance in the earth connection is 2 ohms. Keeping in mind that this value is in series with each line (i.e. 3R has to be included in the expression for zero phase sequence impedance) we can assume that for each transformer:—

$$Z_1 = 0 + j\,0 \cdot 009$$
$$Z_2 = 0 + j\,0 \cdot 009$$
$$Z_0 = 6 + j\,0 \cdot 009$$

When one transformer is operating alone, the total impedance to the fault is

$$Z\,(\text{total}) = 6 + j\,0 \cdot 027 \text{ ohms.}$$

Where two transformers are operating in parallel, the total impedance will be

$$Z_1 = 0 + j\,0 \cdot 0045$$
$$Z_2 = 0 + j\,0 \cdot 0045$$
$$\underline{Z_0 = 6 + j\,0 \cdot 009}$$
$$Z\,(\text{total}) = 6 + j\,0 \cdot 018 \text{ ohms}$$

and, if calculated, it will be found that there is little difference between the two, the resistance value being so large as to swamp the reactance, so that for practical purposes the value of resistance only may be used.

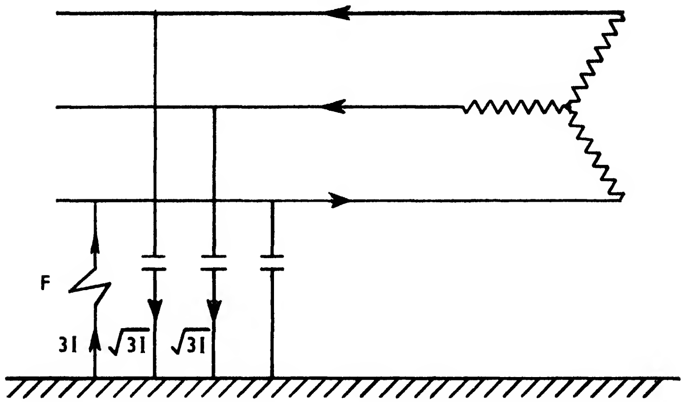


FIG. 20-1.

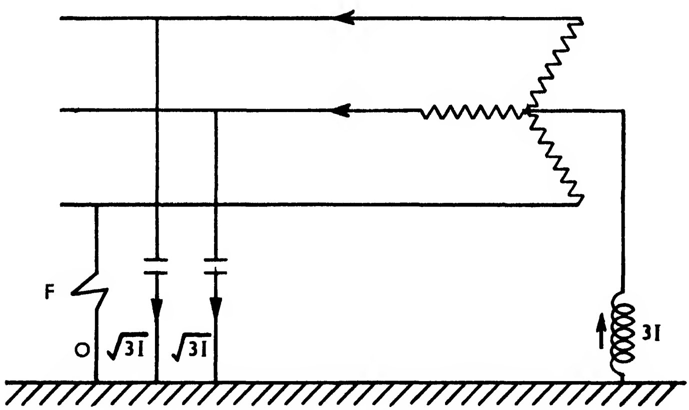


FIG. 20-2.

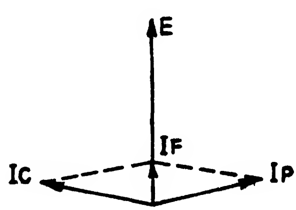


FIG. 20-3.

On systems with an insulated neutral, a fault to earth does not constitute a short-circuit and it may be argued that disconnection is unnecessary. The only current flowing is the capacitance current of the healthy phases, the condition being indicated in Fig. 20-1. In the case of overhead lines, this current may be so small as to render automatic isolation by protective means difficult if not impossible. Such a fault has the effect of raising the voltage of the two healthy lines above the normal to earth and may result in insulation breakdown. Furthermore, it is an unstable condition which may lead to arcing grounds at supporting insulators, causing transient surge voltages to travel in both directions along the line, which may bring about further failure at line insulators or terminal apparatus. By the use of an arc suppression coil as a means of earthing, the danger of arcing grounds is eliminated and under certain conditions the system can be left in service with one line to ground until it is convenient to disconnect and effect repair.

In the condition shown at Fig. 20-1, the capacitance current will lead the voltage of the faulty phase by nearly 90 degrees. It follows that if an inductance of appropriate value is connected in parallel with the capacitances, the current in the fault will be either very considerably reduced or cancelled out. The diagram now becomes that shown in Figs. 20-2 and 20-3, and the initial arc at the fault is immediately extinguished and does not restrike.

It has been stated that the inductance of the coil cancels out the capacitance current. This implies a condition whereby the inductance of the coil must be related to the capacitance of the system and therefore the coil must have an inductance of

$$L=\frac{1}{3\cdot\omega^2\cdot C}\text{ henries}$$

where C=capacitance to earth in farads of each phase

$\omega=2\pi f$

f=frequency in cycles per second.

This leads to some difficulty when, due to varying operational conditions, the capacitance of the network varies from time to time. It can be overcome, however, by using a tapped coil, the appropriate tapping being selected for each change in network conditions.

The condition of being able to allow an earth-fault to persist, therefore, involves the use of a continuously rated coil for the maximum earth-fault current which can pass and this is readily achieved. There is still the danger, however, that a second earth-fault might occur on another line which gives the condition of an interphase fault. To avoid this risk a circuit-breaker may be connected in parallel with the suppression coil, so arranged that the breaker is normally open. After an earth-fault has persisted for a predetermined time, a relay operates to close the circuit-breaker automatically, thus short-circuiting the suppression coil and allowing sufficient uncompensated current to flow for the operation of the protective gear. This scheme is illustrated in Fig. 20-4 and it may be noted that, if necessary, a resistance may be inserted in series with the circuit-breaker, as shown by the broken lines.

If arc suppression coils are to be used on a system it is important that knowledge of this fact and how they are to operate (see pages 697/8) be made

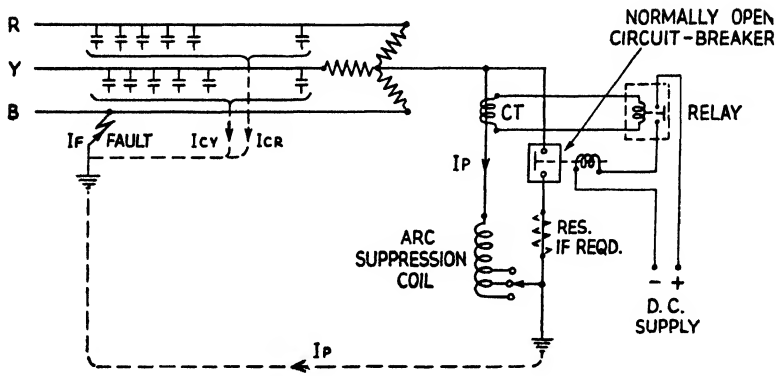


FIG. 20-4.

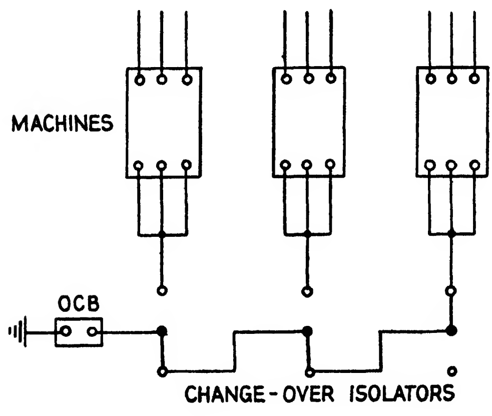


FIG. 20-5.

known to the switchgear manufacturer in order that the latter may offer apparatus of adequate insulation level.

In order to ensure that only one neutral point is earthed where a number of machines or transformers operate in parallel, a series of double throw isolators, connected as shown in Fig. 20-5, can be installed. A very desirable feature is an oil circuit-breaker in the neutral connection which can be opened before an isolator and closed after an isolator. The difficulty with the single circuit-breaker is that it can be given no maintenance unless the neutral is isolated. Duplicate circuit-breakers have been installed on some systems to overcome this difficulty. Alternatively, a circuit-breaker can be connected in each machine neutral before connection to the common earth bar, with interlocks between breakers which will prevent multiple earthing. Circuit-breakers in the neutral connection should have a rated service-

voltage equal to the phase voltage of the three phase system to which it is connected, and should be capable of interrupting the fault current which can flow to earth.

The earth connection proper should receive full consideration, particularly at low-voltages where a low value of resistance is essential if reasonable protective relay settings are to be obtained. Common practice is to bury several earth plates or pipes in parallel order to obtain low resistance values. The cross-section of earth leads must be such as to carry the maximum fault current for the period of time determined by the protective gear. Earth plates, if used, may be copper or cast-iron, from three to six feet square and they should be buried in an upright position with charcoal or crushed coke to a thickness of about a foot or more. The strip connection to the plate or plates should be riveted, or preferably welded, and not soldered, and should be of the same metal to avoid electrolysis. When pipes are used, these should be six to eight feet long and buried as deep as possible; they can be driven quite easily by electric or pneumatic hammers specially designed for the purpose.

A low resistance is essential to keep down the potential gradient in the earth surrounding the plates or pipes under fault conditions. Most of the resistance exists in the immediate vicinity of the plates or pipes. Regular checking of the earth contact resistance is essential. It is by no means constant and alters with the amount of moisture in the soil and is therefore subject to seasonal variations.

At this point it is of interest to note the existence of a very high-speed ammeter developed by Messrs. Everett Edgcumbe & Co. Ltd., which, connected in the neutral via a suitable current transformer, acts as a ground fault detector. The instrument, shown in Fig. 20-6, has a high-speed rectifier-operated moving coil movement and, when operating, the pointer is driven to the point of maximum current in 5 cycles (0·1 sec.), at which

FIG. 20-6.—*High-speed ammeter (Everett Edgcumbe & Co. Ltd.)*

point it is held by a magnetic clutch until reset by hand. Damping is such that there is no overswing. On interconnected systems an instrument of this type installed at each system neutral provides a series of readings on the occurrence of a ground fault, thus showing the distribution of fault current. From this a close approximation can be determined as to the location of the fault.

The connections for this instrument are shown in Fig. 20-7. Normal full scale deflection is at 5 or 10 amperes but the sensitivity can be increased to give full scale deflection at 0·5 or 1·0 amperes by operating the press key.

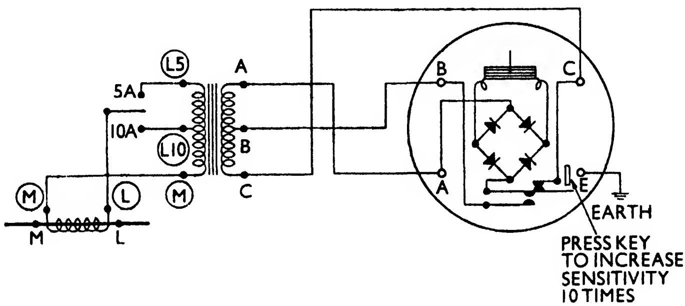


FIG. 20-7.—*Connections for high-speed ammeter in neutral (Everett Edgcumbe & Co. Ltd.).*

Incidentally, it may be noted that this instrument (connected one in each line) is of value in short-circuit testing (see chapter V) as it enables immediate readings of the short-circuit current to be made without waiting while oscillograph records are scaled.

It was noted earlier that on systems with a free neutral, one line may be down to earth with the two healthy lines continuing in service. Such a condition may not always be desirable, at least if allowed to persist for any length of time, and Messrs. Everett Edgcumbe & Co. Ltd., have produced a protective system which provides an artificial neutral point through three star-connected condensers and a protective relay system comprising a fault detector unit, a moving coil operating relay and a time delay unit. The system used is shown in Fig. 20-8 and operationally there will be no voltage between the star point and earth when conditions are normal but when a line to earth fault occurs, the artificial neutral will be displaced and a voltage appear between the star point and earth, a voltage which is utilised to operate the relay system. If the neutral of the transformer star winding is available but *not* earthed, the system can be applied using one condenser only connected in the star point as shown inset in Fig. 20-8. To ensure that the system does not cause unnecessary operation on transient faults, the time delay relay is provided with adjustable settings up to 20 seconds.

A useful feature of this system is the provision of a magnetic counter to register the number of faults detected and means for testing the apparatus (other than the condensers) by producing an artificial fault. In areas subject to lightning or other causes of surge voltage, a spark gap can be fitted across

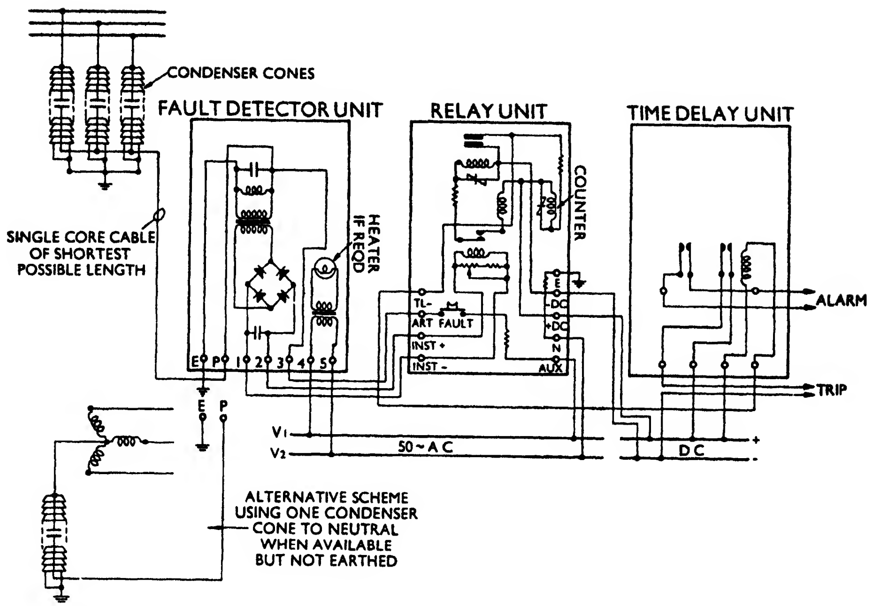


FIG. 20-8.—*Neutral voltage displacement protective system (Everett Edgcumbe & Co. Ltd.).*

the earthy end of each condenser and earth, the gap being set to break down at approximately 700 volts. By this means the relay system is protected against high-voltage surges.

Note.—The reader is referred to the J. & P. Transformer Book for details of earthing by neutral compensator on systems where a neutral is not available.

BIBLIOGRAPHY

Electrical Power, A. T. Starr (Pitman & Sons).

Switchgear Practice, A. Arnold (Chapman & Hall).

The J. & P. Transformer Book, S. Austen Stigant, H. Morgan Lacey and A. C. Franklin (Johnson & Phillips, Ltd.).

"LINE PROTECTION BY PETERSEN COILS," H. W. Taylor and P. F. Stritzl, "Journal I.E.E.," Vols. 82 and 83, Nos. 496 & 503, 1938.

"SAFEGUARDS AGAINST INTERRUPTION OF SUPPLY," H. W. Clothier, B. H. Leeson and H. Leyburn, "Journal I.E.E.," Vol. 82, No. 497, May 1938.

"THE PETERSEN EARTH COIL," S. Austen Stigant, "The Electrical Engineer," July 9th, 1937.

"DISTRIBUTION OF CAPACITANCE CURRENT," S. Austen Stigant, "The Electrical Times," July 4th, 1935.

CHAPTER XXI

SURGE PROTECTION

CHAPTER XXI

SURGE PROTECTION

Overvoltages which appear on electrical systems can be broadly described as internal or external. In more detail they are as follows:—

Internal overvoltages. These originate in the system itself and may be transient, dynamic or stationary. Those of a transient nature will have a frequency unrelated to the normal system frequency and will persist for a few cycles only.

They can be caused by the operation of circuit-breakers when switching inductive or capacitive loads, "current chopping" when interrupting very small currents (see Chapter II) or by the sudden earthing of one phase of a system operating with an insulated neutral.

Dynamic overvoltages occur at normal system frequency and persist only for a few seconds. They may be caused, for example, by the disconnection of a generator which overspeeds, or when a large part of the load is suddenly removed.

Stationary overvoltages also occur at system frequency but they may persist for some time, perhaps hours. Such a condition can arise when an earth-fault on one line is sustained, as indeed it may intentionally be when the neutral is earthed through an arc-suppression coil as described in Chapter XX, thereby leading to overvoltages on the sound phases.

Overvoltages as described above rarely exceed three to five times the normal phase to neutral *peak* voltage of the system and subject to apparatus having an adequate insulation level, should be relatively harmless.

External overvoltages. These overvoltages are produced by atmospheric discharges such as static charges or lightning strokes and are therefore not related to the system. They are often of such magnitude as to cause considerable stress on the insulation and, in the case of lightning, will vary in intensity depending on how directly the line is struck, i.e. directly by the main discharge, directly by a branch or streamer, or by induction due to a flash passing near to but not touching the line.

Switchgear specifications describe two classifications for an installation namely one which is "electrically exposed" resulting in the apparatus being subject to overvoltages of atmospheric origin, and another which is "electrically non-exposed" and therefore not subject to this type of overvoltage. The first of these is generally recognised as an installation connected directly to overhead transmission lines, e.g. outdoor switchgear or transformers but it can apply to indoor gear connected to overhead lines via outdoor to indoor through bushings (see Fig. 8-19 Chapter VIII) or by a short length of cable. The second classification is one usually associated with underground cable networks and the switchgear will normally be of the indoor type.

Because of the stresses due to external overvoltages, it is now required that certain switchgear and transformers shall be impulse tested, and this is the case for circuit-breakers of the outdoor type for service voltages of 22 kV and above (see Clause 41 B.S. 116:1952). It is also intimated that suitable protective devices be installed to ensure that the amplitude of the surges imposed on the terminals of outdoor apparatus is limited to a value not exceeding 80 per cent of the impulse test level.

These precautions may also be necessary to protect indoor gear when, as indicated earlier, this is associated with overhead transmission.

The purpose of this chapter is to consider in outline the nature of surges due to lightning and the function and features of diverter design.

A surge is the movement of a charge that is suddenly released in a conductor and which travels along that conductor in the form of a wave. The potential of a conductor being a measure of charge density, it follows that the potential wave must be accompanied by a current wave. The shape of the voltage wave is affected by a number of factors, such as inductance and capacitance. Thus, on a line where the impedance is purely inductive, the front of the wave would be almost vertical, while if the impedance is purely capacitive then the wave front would slope steeply away from the vertical. From this it is clear that the wave-shape is affected by the relation between the L and C values, this relationship being expressed as the surge impedance,

$$Z = \sqrt{L/C}$$

where Z = Surge impedance in ohms
L = Inductance in henries
C = Capacitance in farads

As the wave travels along the line its front is modified by the inductance of the line and the distributed capacitances to earth. It may be further modified by the capacitances of bushings, insulators, etc., which the wave encounters on its journey, thus reducing the steepness of the wave-front.

A further point has also to be considered, namely that when the travelling wave reaches a point where there is a change in surge impedance of the line, reflection of the wave will occur, reflection being whole or partial depending on the amount of change in surge impedance. In the case, for example, of an open-ended feeder, the change in surge impedance is infinite and a travelling wave would be totally reflected, with the result that the pressure would be practically doubled at the point of reflection due to the front of the wave being reversed and adding itself to the remainder of the wave still travelling forward; the duration of doubled value will depend on the length of the wave-tail. In other cases, such as one where an overhead line is joined to an underground cable, the change in surge impedance is not infinite and the reflection will depend on the relative values of the impedances of the overhead line and the cable.

It is clear that surges when travelling along a line will, at some point reach terminal apparatus such as cable boxes, transformers or switchgear, and, unless some means is provided to release the surge, there is a danger of a breakdown of the insulation of the terminal apparatus, unless the insulation level of the latter is high enough to be invulnerable. On smaller systems

this could be an expensive solution and, therefore, it becomes necessary to install lightning arrestors or surge diverters.

SURGE DIVERTERS

At one time, the usual practice was to put choke coils in the line, coupled with horn gaps connected between line and earth. This apparatus provides some protection but in fact, could add to the dangerous conditions by reflecting the surge wave and permitting considerable power current to flow to earth following discharge. To be really effective a surge diverter should reduce the surge voltage crest and at the same time absorb the transient energy to an extent sufficient to prevent reflection.

Two characteristics are essential :—

(1) The surge voltage appearing at the diverter terminals must be limited to a value which will safeguard the insulation of terminal apparatus.

(2) The diverter must, after discharge, cease to carry current, i.e. it must become an insulator again.

Diverters of this type may be correctly described as "valve arrestors", the characteristics being those of a "safety valve", which is normally closed but opens in the event of dangerous overvoltage, and, after relieving the system of these voltages, closes again. After operation, the diverter must be in a condition to accept and deal with ensuing surges, i.e. there must be no failure of the diverter itself.

In practice, diverters which provide these features comprise one or more air gaps mounted in series with non-linear resistors, the function of the air gaps being to keep the circuit through the arrestor to earth open under all normal power frequency conditions, but to flash over and close the circuit when abnormal voltages appear at the diverter terminals.

The non-linear resistances must absorb surge energy and in conjunction with the air gaps suppress the flow of power current. These resistances have the important characteristic that the resistance value decreases very rapidly as the current through the material increases.

It follows that they can carry very large currents without the voltage drop across them rising to an excessive value. The residual voltage across the diverter therefore remains low, thus limiting the voltage on the line to a value which will not damage the system insulation. As soon as the surge has been discharged the voltage across the diverter tends to fall and the current therefore to decrease. The resistance of the resistor then begins to increase, and the flow of power current due to the system voltage is then reduced, and within a short time (usually less than one half-cycle of system frequency), is sufficiently reduced to be interrupted by the spark gaps as the system voltage passes through zero. At this point, the diverter resumes its normal non-conducting condition and is ready for further operation.

The successive stages of diverter operation, are shown diagrammatically in Fig. 21-1. At (*a*) we note the front of a surge wave approaching the diverter which may be assumed to be protecting terminal apparatus not shown, but connected to the line to the left of the diverter. At (*b*) the surge has reached the diverter and, in about 0·25 microsecond, the voltage has reached a value sufficient to break down the spark gaps and, as shown at (*c*), surge current flows to earth. As the crest of the surge approaches the point of the

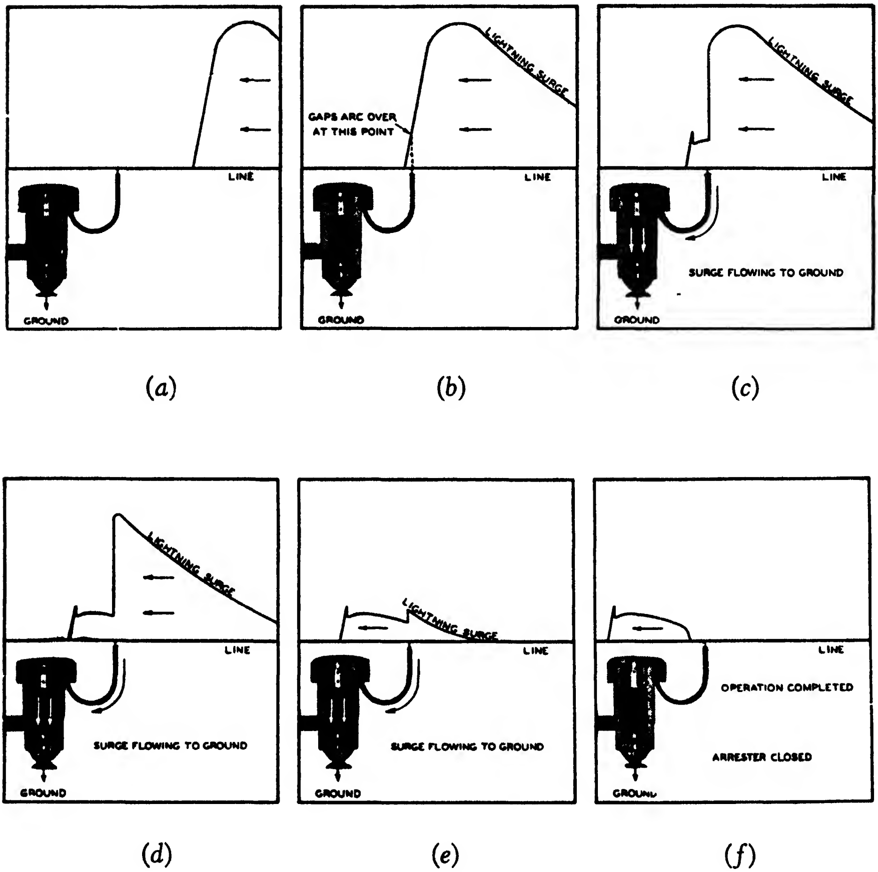


FIG. 21-1.
Stages of surge diverter operation.

line at which the diverter is connected, so the voltage applied increases and, just as rapidly, the resistance of the element decreases, thus permitting further surge energy to discharge and so limiting the voltage impressed on the terminal apparatus to a safe value—as indicated by the lower value of voltage beyond the diverter line connection. At (*d*) the crest of the wave is shown passing the terminal point and, at (*e*), the tail of the wave is shown approaching. At this stage the voltage is decreasing and, in consequence, the current to earth decreases while the resistance increases, reaching a stage when the current flow is interrupted by the spark gaps and thus "sealing" the diverter as shown at (*f*). The whole of this operation takes place in a matter of microseconds and, in a typical case shown in Fig. 21-2 in 30 microseconds.

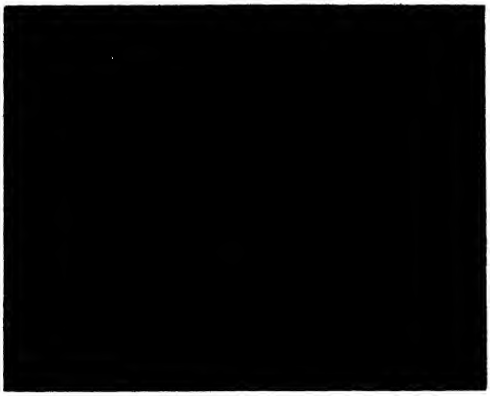


FIG. 21-2.
Typical oscillogram of surge diverter operation.

This oscillogram depicts the operation of a 3 kV diverter with an average rate of voltage rise at the beginning of arrestor discharge of 50 kV per microsecond and the average rate of current rise, after the beginning of the discharge, of 150 amperes per microsecond to a crest of 1 520 amperes.

This steepness of wave-front is typical of lightning surges and in the wave-front impulse sparkover test in B.S.2914:1957 (Surge Diverters) it is laid down that the steepness must comply with values listed in Table 4 of that specification and which vary according to the rated diverter voltage, e.g. 17 kV per microsecond for a 1·25 kV diverter to 1 200 kV per microsecond for a 245 kV diverter.

This standard specification provides for a number of type tests which must be made as follows:—

Test No. 1. 1/50 impulse sparkover test.
, ,, 2. Wave-front impulse sparkover test (mentioned above).
, ,, 3. Peak discharge residual voltage at low current.
, ,, 4. Peak discharge residual voltage at rated diverter current.
, ,, 5. Operating duty test.
, ,, 6. Impulse current withstand test.

For test No. 1. it is noted that this is described as 1/50 impulse sparkover test. The significance of the term 1/50 is that it denotes both the steepness of the wave-front and the decline of the wave-tail to a value equal to one-half the peak value and both figures are in microseconds. This is perhaps better understood by studying Fig. 21-3 which shows how, in the left hand wave form the front reaches its peak voltage (100 kV) in 1 microsecond and the tail has fallen to 50 kV, i.e. one half of the peak value in 50 microseconds. In the right hand curve the tail falls to 50 kV in 20 microseconds and is therefore designated a 1/20 wave.

For tests Nos. 4 and 5 a current wave of 8/20 microseconds has to be passed, indicating a tail of just over twice the duration of the front. In

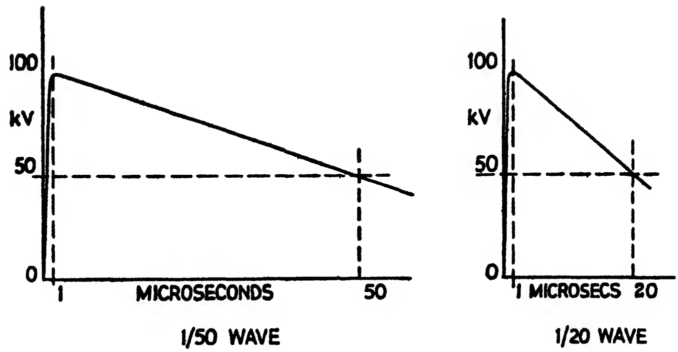


FIG. 21-3.—*Typical impulse wave forms*

test No. 6, rectangular current impulses* of a magnitude dependent on the rated diverter current must be passed 20 times and the maximum current has to be maintained for a period of time which is again related to the rated diverter current.

Full details of all the tests are given in B.S.2914:1957, and examples of oscillographic records on representative surge diverters will be noted later.

Surge diverters are rated in terms of voltage and current, the rated diverter voltage being the highest r.m.s. value of power frequency voltage, measured between the line and earth terminals of the diverter, at which the diverter is designed to work continuously, while the rated diverter current is that value of impulse current used in test Nos. 4 and 5 and can be one of four standard ratings.

To select a surge diverter of suitable voltage rating for a given system voltage will require a knowledge of the system earthing condition, i.e. whether "effectively earthed" or "non-effectively earthed" as defined in many British Standards. To be "effectively earthed" all transformer star-connected windings should have their neutrals solidly earthed direct i.e., a multiple earthed system and for this condition the line to earth voltage will not exceed 80 per cent of the highest system voltage†. A "non-effectively earthed" system on the other hand includes those with a limited number of solidly earthed neutrals and those earthed through a resistor or reactor of low impedance or an arc suppression coil, and here the line to earth voltage under fault conditions will be greater than 80 per cent but will not exceed 100 per cent of the highest system voltage (110 per cent of nominal).

On unearthed systems it is possible for line to earth voltages higher than 100 per cent of the highest system voltage to appear but it is usual practice to assume that this is an abnormal condition and select a diverter on the 100 per cent basis. It is a choice between risking a diverter failure or going to the next higher rating with a substantially reduced degree of protection.

* *B.S. 2914 defines a rectangular impulse wave as a unidirectional wave of voltage or current which rises rapidly to a maximum value, remains substantially constant for a specified period and then falls rapidly to zero. See Fig. 21—14 for example.*

†*B.S. 77 defines the highest system voltage line-to-line as a value which may be 10 per cent higher than the nominal line-to-line voltage.*

As an example of rated diverter voltage selection, it may be assumed that it is required to choose suitable diverters for 6·6 and 11·0 kV systems, under the alternative conditions "effectively earthed" and "non-effectively earthed", noting that a choice will lie between four standard ratings from Table 4, B.S. 2914:1957, namely 5·9, 7·3, 10·0 and 12·5 kV rated diverter voltages. The determination would be as follows:-

6·6 kV (nominal) system

(a) 110% of nominal = 7·26 kV—non-effectively earthed
(b) 80% of (a) = 5·81 kV—effectively earthed

For (a) therefore a diverter rated 7·3 kV will be required, whereas for (b) the lower rating of 5·9 kV will suffice.

11 kV (nominal) system

(a) 110% of nominal = 12·1 kV—non-effectively earthed
(b) 80% of (a) = 9·68 kV—effectively earthed

For (a) therefore a diverter rated 12·5 kV will be required, wheareas for (b) one rated at 10 kV will suffice.

There are four standard diverter current ratings, 10,000 5,000 2,500 and 1,500 amperes, and these represent the values of impulse current used in tests 4 and 5. In B.S. 2914:1957 it is recommended that these alternative current ratings should be employed as follows:—

(1) 10 000 amperes rating (station type) for the protection of major power stations and substations in which the frequency of occurrence of lightning strokes to earth is known to be high. For systems having a normal system voltage greater than 66 kV, they are used exclusively*.

(2) 5 000 ampere rating (line or intermediate type) for the protection of other power stations and large substations on systems where the voltage does not exceed 66 kV.*

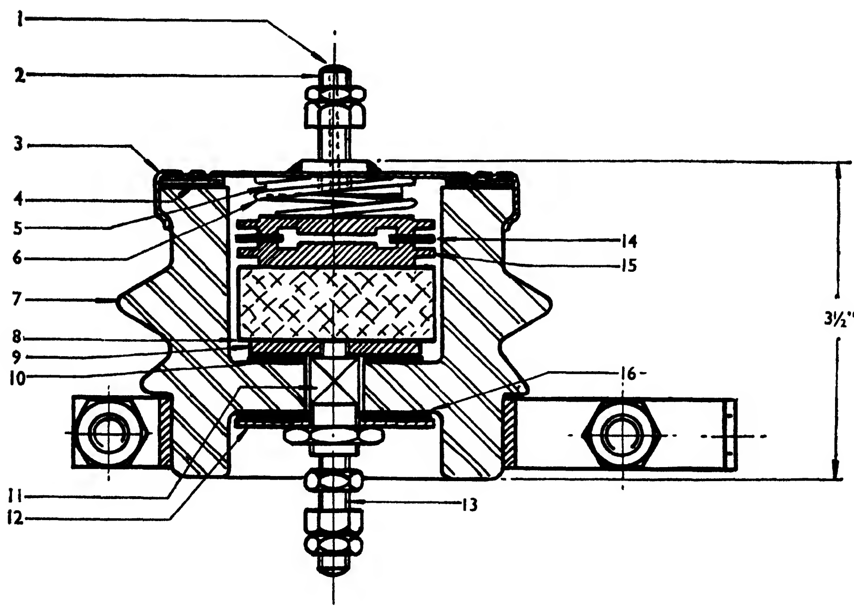
(3) 2 500 ampere rating (rural or secondary type) for the protection of small substations where higher current ratings are not economically justified. This rating is not used on systems above 22 kV.

(4) 1 500 ampere rating (rural or secondary type) for the protection of rural distribution systems where diverters are installed at frequent intervals to protect small transformers. When B.S.2914 was prepared in 1957, this rating was limited to systems up to and including 22 kV but it is now available for systems up to 33kV and is used extensively at this voltage.

These values of current are those required by test No. 5. to be applied 30 times in succession without damage to the diverter, whilst subjected to its rated voltage. For a limited number of operations however, most diverters will pass, without damage, currents considerably in excess of the rated value and in the published literature of manufacturers withstand currents of 65 000 to 100 000 peak amperes (5/10 microsecond wave) are noted usually for two successive applications. It is of interest to note that the General Electric Company state in their literature that based on measurements of currents flowing in surge diverters in service on rural unshielded

* *These two statements are in accord with B.S. 2914:1957 but it is understood that 5 000 ampere diverters are now becoming available for system voltages up to 132 kV.*

FIG. 21-4.—*Surge diverter rated at 660 volts (The General Electric Co. Ltd.)*



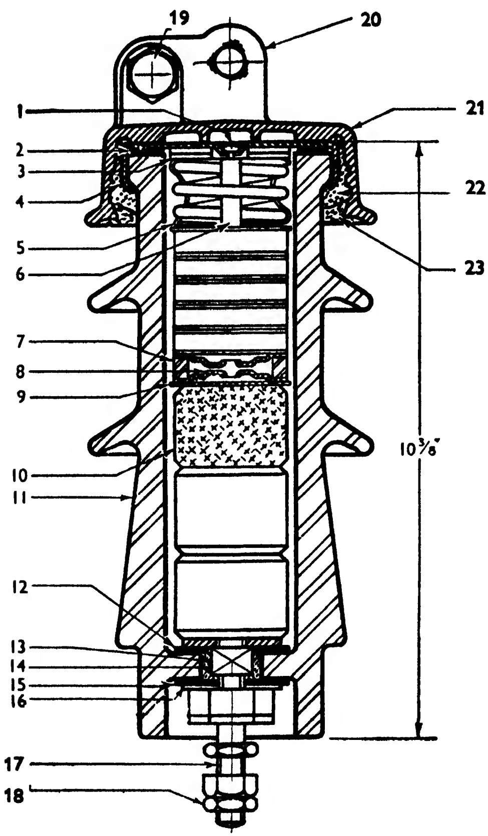
1. EXHAUSTING HOLE—SOLDERED.
2. BRASS TERMINAL STUD.
3. COPPER CAP SPUN ON BODY
4. RUBBER SEALING WASHER.
5. SPRING CENTRALISING DISC.
6. COMPRESSION SPRING
7. PORCELAIN BODY.
8. NON-LINEAR RESISTOR.
9. CONTACT PLATE.
10. RUBBER SEALING WASHER.
11. BRASS TERMINAL STUD.
12. BRASS WASHER AND LABEL.
13. CONNECTION STEM.
14. MICA WASHER.
15. SPARK GAP DISC.
16. SEALING WASHER.

FIG. 21-5.—*Sectional view of low-voltage surge diverter. (The General Electric Co. Ltd.).*

lines, only 0·5 per cent showed discharges in excess of 30 000 amperes and that the great majority were in the range of 200—4 000 amperes. Elsewhere it has been stated that in Great Britain, at least 90% of all currents as they flow in diverters, are in the order of 1 000 amperes or less. High withstand current tests are not included in B.S.2914 but do appear in American and I.E.C. standards.

Surge diverters of the type described are available for all system voltages from 300 volts to 345 kV and typical of one for use on low voltage systems is the 660 volt diverter by the General Electric Company shown in Figs 21-4 and 21-5.

Typical of diverters in the 1 500 ampere (rated discharge current) class and available for systems voltages up to 33 kV is that shown in Fig. 21-6.



1. EXHAUSTING HOLE, PLUGGED AND SOLDERED.
2. RUBBER SEALING WASHER.
3. SPACING DISC.
4. COPPER CAP SPUN ON BODY
5. COMPRESSION SPRING.
6. COPPER SHUNTS.
7. SPARK GAP SPACER.
8. SPARK GAP DISC.
9. CONTACT PLATE.
10. NON-LINEAR RESISTOR.
11. PORCELAIN BODY.
12. RUBBER WASHER.
13. BRASS TERMINAL STUD.
14. HOLE IN PORCELAIN, SEALED WITH COMPOUND.
15. SEALING WASHER
16. BRASS WASHER.
17. COPPER STUD.
18. EARTH CONNECTION.
19. ADJUSTABLE LINE CONNECTING CLAMP.
20. LUG FOR LINE SUSPENSION CLAMP.
21. GUNMETAL CAP.
22. KEENS CEMENT.
23. PORTLAND CEMENT.

FIG. 21-6.—*Sectional view of surge diverter for system voltages up to 33 kV*

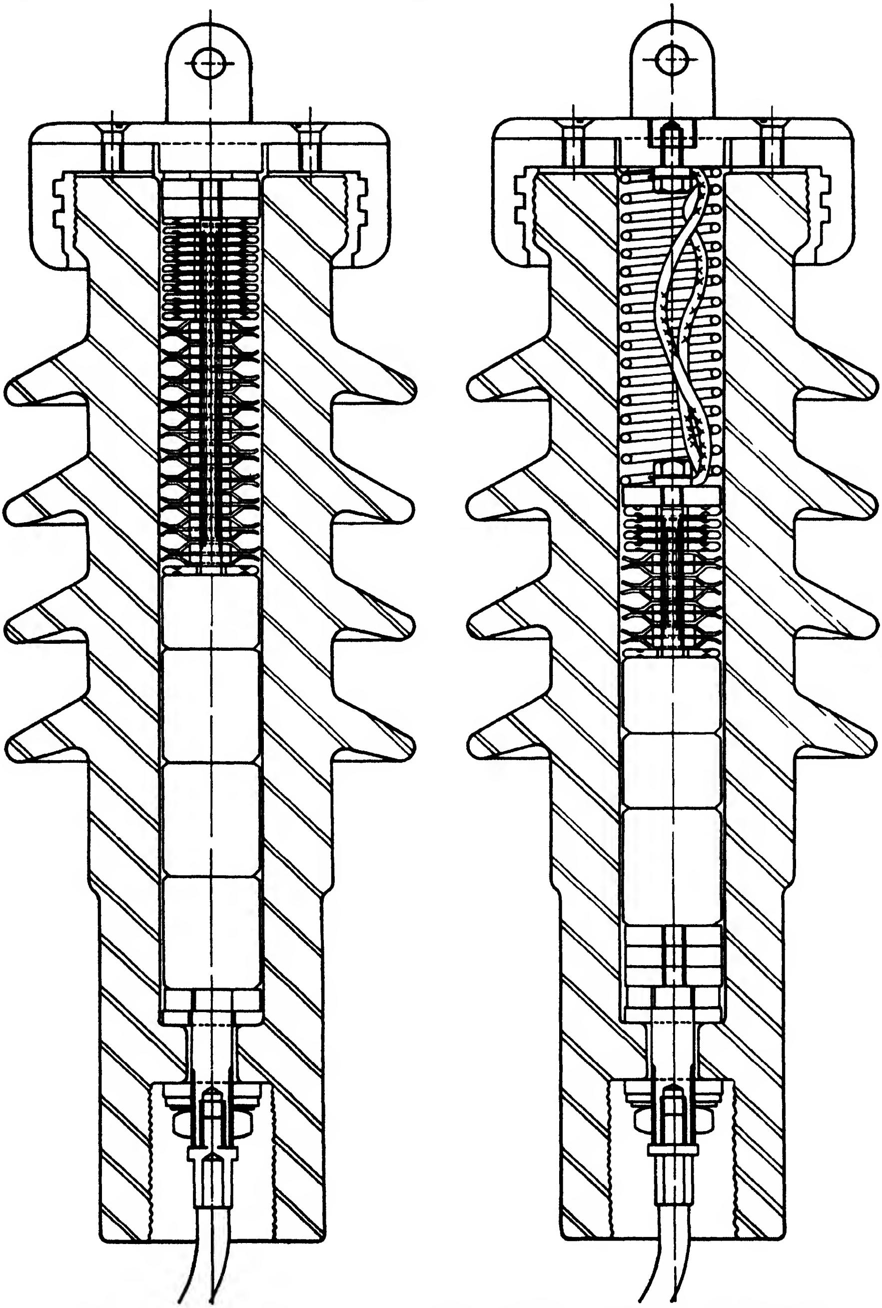


FIG. 21-7.—*Sectional views of typical designs for 2 500 ampere surge diverters 5·9 kV and 10 kV.*

Designs for diverters rated at 2 500 amperes for rated diverter voltages of 5·9 kV and 10 kV respectively would be generally as shown in Fig. 21-7.

In this illustration, as in Fig. 21-6, will be seen the spark-gap components and the non-linear resistors forming the series circuit between line and earth, and all maintained in contact under pressure by the relatively large compression spring. The external appearance of the 10 kV diverter is indicated in Fig. 21-8.

On page 715 reference has been made to the tests detailed in B.S.2914: 1957 with which surge diverters must comply. Oscillographic records of some of these tests are reproduced in Fig. 21-9 to 21-14, these being facsimile reproductions from K.E.M.A. Report No. 2642-60 for research tests on diverters similar to the designs shown in Fig. 21-7.

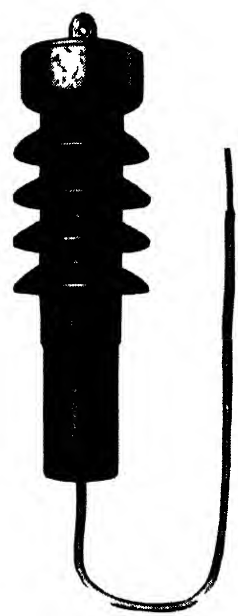
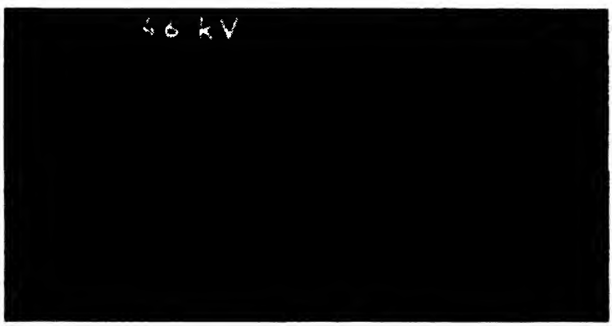


FIG 21-8.—*External view of 10 kV 2 500 ampere surge diverter.*

APPLIED 1/60/μ SEC IMPULSE VOLTAGE WAVE. TIME CALIBRATION 250 kC/S.

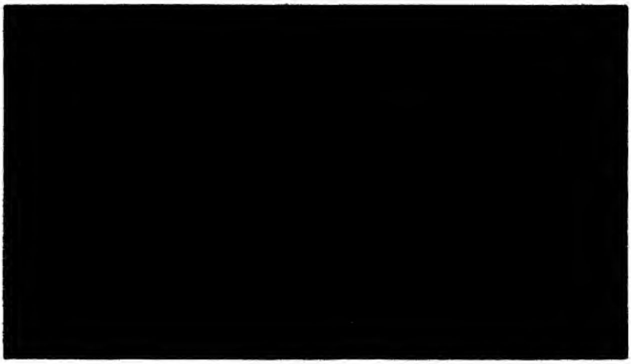
FIG. 21-9.—*1/60 microsecond impulse sparkover test.*



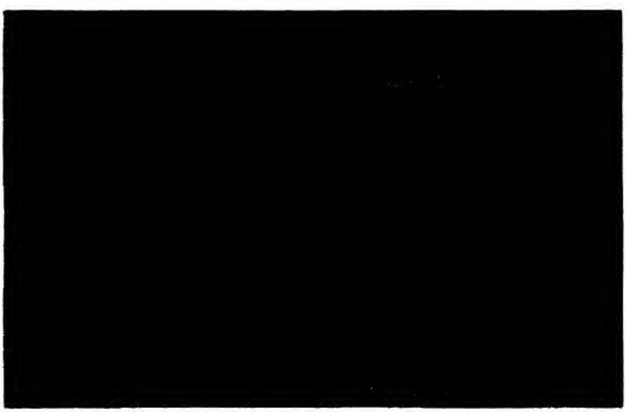
WAVE-FRONT IMPULSE SPARKOVER OSCILLOGRAM OF 10 kV R.M.S. DIVERTER. NOMINAL STEEPNESS 83 kV/μ SEC TIME CALIBRATION 1000 kC/S.

WAVE-FRONT IMPULSE SPARKOVER OSCILLOGRAM OF 5·9 kV R.M.S. DIVERTER. NOMINAL STEEPNESS 49 kV/μ SEC

FIG. 21-10.—*Wave-front impulse sparkover tests.*



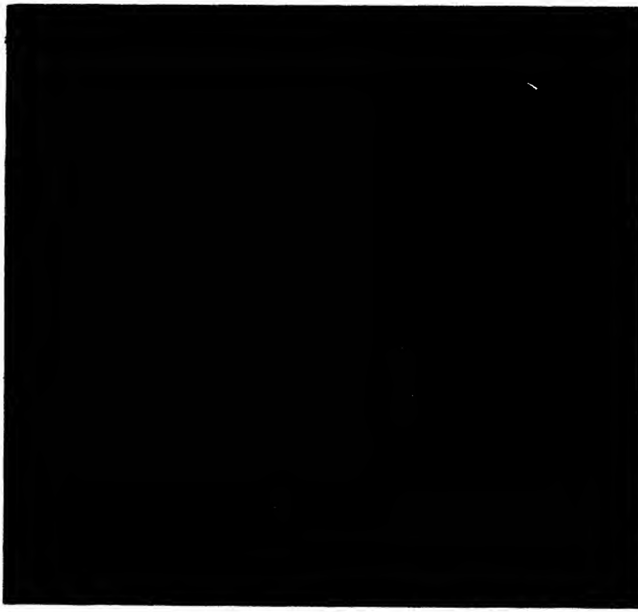
PEAK DISCHARGE RESIDUAL VOLTAGE AT LOW CURRENT OF THE 10 kV R.M.S. DIVERTER.



PEAK DISCHARGE RESIDUAL VOLTAGE AT LOW CURRENT OF THE 4·0 kV. R. R.M.S. DIVERTER.

FIG. 21-11.—*Peak discharge residual voltage tests at low current.*

TIME CALIBRATION 250 kc/s.



PEAK DISCHARGE RESIDUAL VOLTAGE AT RATED CURRENT OF 5·9 kV R.M.S. DIVERTER BEFORE AND AFTER OPERATING DUTY TEST.

PEAK DISCHARGE RESIDUAL VOLTAGE AT RATED CURRENT OF 10 kV R.M.S. DIVERTER BEFORE AND AFTER OPERATING DUTY TEST.

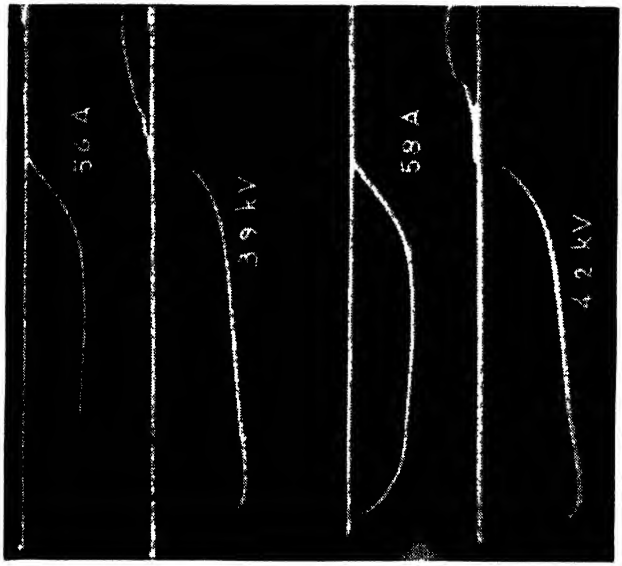
FIG. 21-12.—*Peak discharge residual voltage tests at rated diverter current.*

30TH IMPULSE OF THE OPERATING DUTY TEST ON THE 10 kV R.M.S. DIVERTER.

25TH IMPULSE OF THE OPERATING DUTY TEST ON THE 5·9 kV R.M.S. DIVERTER.

FIG. 21-13.—*Operating duty test.*

TIME CALIBRATION 10 kc/s.



2ND AND 20TH OSCILLOGRAM OF THE CURRENT WITHSTAND TEST ON A ⅛″ RESISTOR.

4TH AND 20TH OSCILLOGRAM OF THE CURRENT WITHSTAND TEST ON A 1½″ RESISTOR.

FIG. 21-14.—*Impulse current withstand test.*

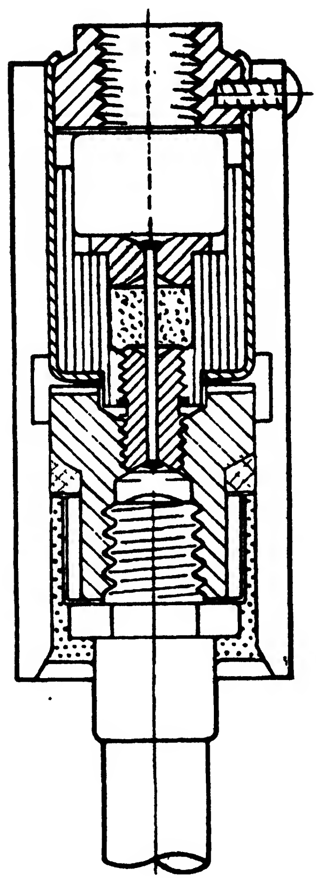


FIG. 21-15.—*Earth disconnect device graded to discriminate with 10 ampere quick acting expulsion fuses. (EMP Electric Ltd.).*

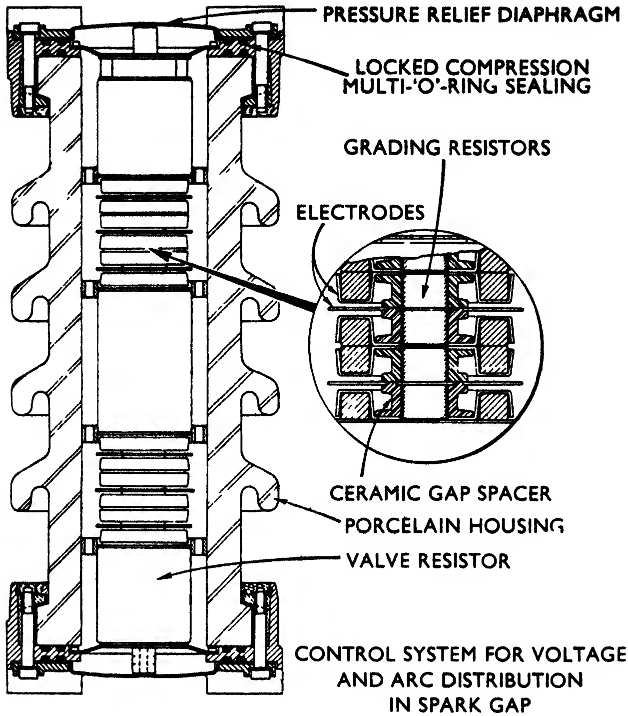


FIG. 21-16.—*Cross-section of unit stack in* 10 000 *ampere surge diverter.* (*EMP Electric Ltd.*).

In the 5 000 ampere class of diverter, EMP Electric Ltd., have produced a design which includes system voltage ratings from 600 volts to 33 kV for effectively earthed systems and 440 volts to 18 kV for non-effectively earthed systems. Bracket mounted diverters include an earth disconnect device designed so that if a divertor failure should occur the earth lead is ejected to disconnect the arrester before damage can occur.

This arrangement has been designed in its standard form to discriminate with line expulsion type fuses of 25 amperes or above but where service continuity is to be ensured with smaller expulsion type line fuses, e.g. 10 amperes quick acting, a graded disconnect can be provided as shown in Fig. 21-15 which will disconnect a damaged diverter before the line fuses melt.

This same manufacturer has a range of 10 000 ampere class diverters for a wide range of system voltages extending up to 400 kV. At the higher voltages, each diverter comprises a number of stacks in series and up to 4 stacks may be used in a single column up to about 300 kV. For higher voltages the assembly will comprise two columns of multiple stacks.

Fig. 21-16 is typical of a stack as used and here it will be noted that valve resistors are placed top, bottom and central with two intervening

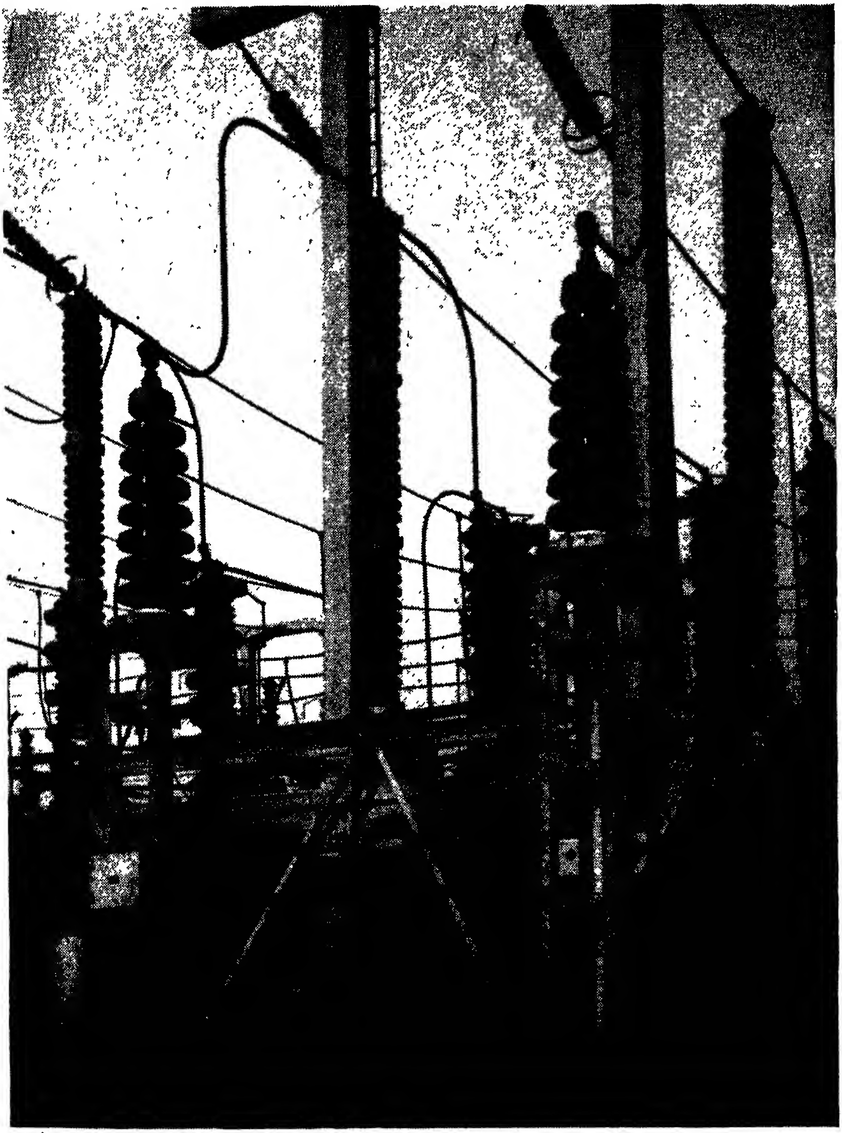


FIG. 21-17.—*Multi-unit station type surge diverter, 121 kV line to ground rating, at Stella Power Station 132 kV substation. (EMP Electric Ltd.). (Photograph by courtesy of the C.E.G.B., N.E. Division and Messrs. Merz & McLellan Consulting Engineers).*

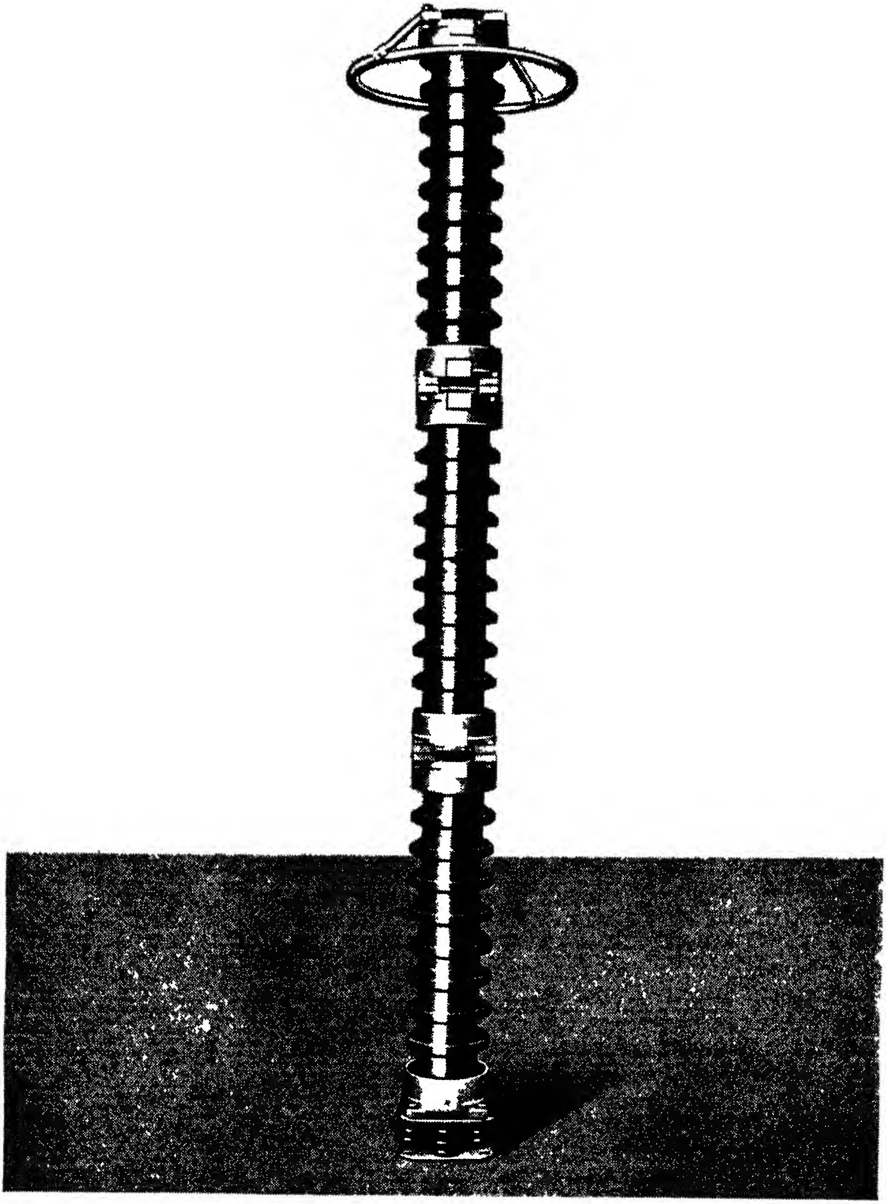


FIG 21-18 —*Multi-unit station type surge diverter, 145 kV rating (EMP Electric Ltd)*

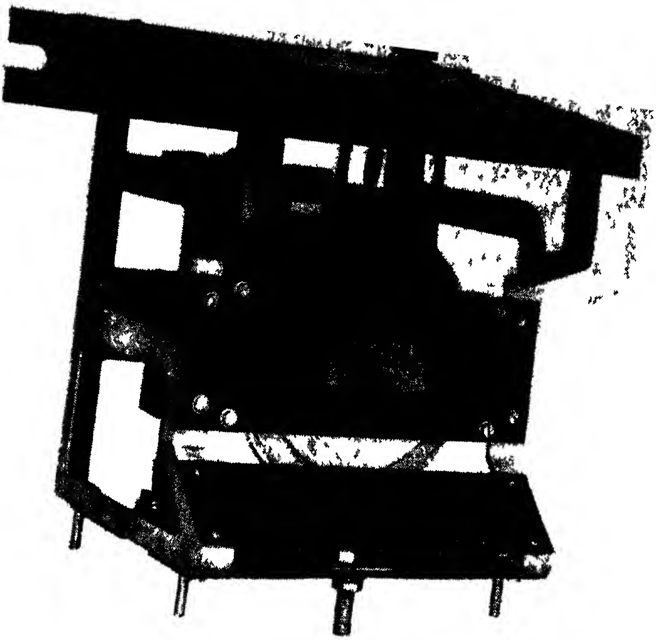


FIG 21-19 —*View of surge counter with cover removed (The General Electric Co Ltd)*

blocks of spark gaps This illustration also shows a pressure diaphragm fitted at each end which is a feature of diverters of this make for very high voltages The diaphragm acts as a safety device to function only if, for some unforseen reason, the diverter should lose its ability to interrupt power follow-current, a circumstance which may permit the full system short-circuit current to develop through the diverter This would cause a considerable gas pressure to develop, due to the concentration of energy within the porcelain, and may cause the latter to shatter The diaphragm is designed to burst under high-pressure, venting and dispersing the gas at high-speed via exhaust vents

Inset in this illustration is shown how a control system is introduced in the spark gap assemblies for voltage and arc distribution This gives a uniform distribution of arc energy over the whole spark gap surface, and control of the power frequency voltage distribution The latter is achieved by the non-linear ceramic grading resistors shunting the gap electrodes.

Typical of very large arrestors are those shown in Figs 21-17 and 21-18

SURGE COUNTERS

It is not easy to assess the functioning of surge diverters as there is nothing to indicate operation or otherwise. There are however devices available known as surge counters which, when inserted in the earth lead of the diverter, will record each operation on a counter or on a paper disc.

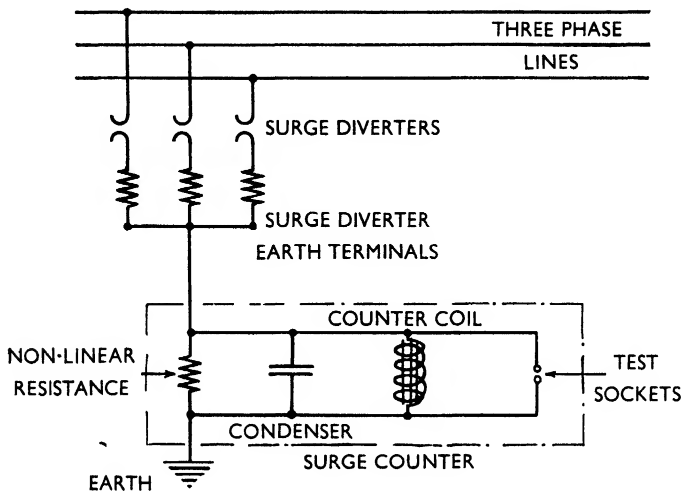


FIG. 21-20.—*Typical circuit arrangement of surge diverters and counter. (The General Electric Co. Ltd.).*

One such device is that shown in Fig. 21-19, the diagram of the circuit arrangement being that shown in Fig. 21-20.

The non-linear resistor in this arrangement has a high surge current rating while the capacitor has a surge voltage strength well in excess of the maximum voltage developed across the resistor when the associated diverter is discharging the heaviest surge current. The operating coil will also withstand this voltage.

The cyclometer dial counter seen in Fig 21-20 is visible through a window in the cover which has been removed in this illustration.

The operation of this counter is such that when an excessive over-voltage occurs on the line causing the diverter to operate, the surge is discharged to earth through the surge counter. A small part of the energy thus discharged is used to charge the capacitor which in turn discharges through the operating coil of the counter to register the occurrence.

The voltage-dependent property of the non-linear resistor limits the maximum voltage which is developed across the capacitor and coil and presents a high leakage resistance in parallel with the coil during the discharge period. A test socket permits the counter mechanism to be tested by means of an exterior source of supply, a 60 volt dry battery being suitable for the purpose. The base of each diverter must be insulated from earth to withstand about 3 kV peak.

In another device a paper disc is revolved, after the manner of a chart recorder, in a spark gap which is in the earth lead of the surge diverter. The construction is shown in Fig. 21-21 from which it will be seen that the paper disc is driven by a small synchronous motor which is connected to any convenient l.v., a.c. supply. The disc has an appropriately divided scale of days and hours and makes one revolution per week.

When the surge diverter operates, the spark gap flashes over and a hole is punctured in the paper disc. The size of the hole will be approximately related to the magnitude of the surge and its position will indicate the time and on what day it occurred.

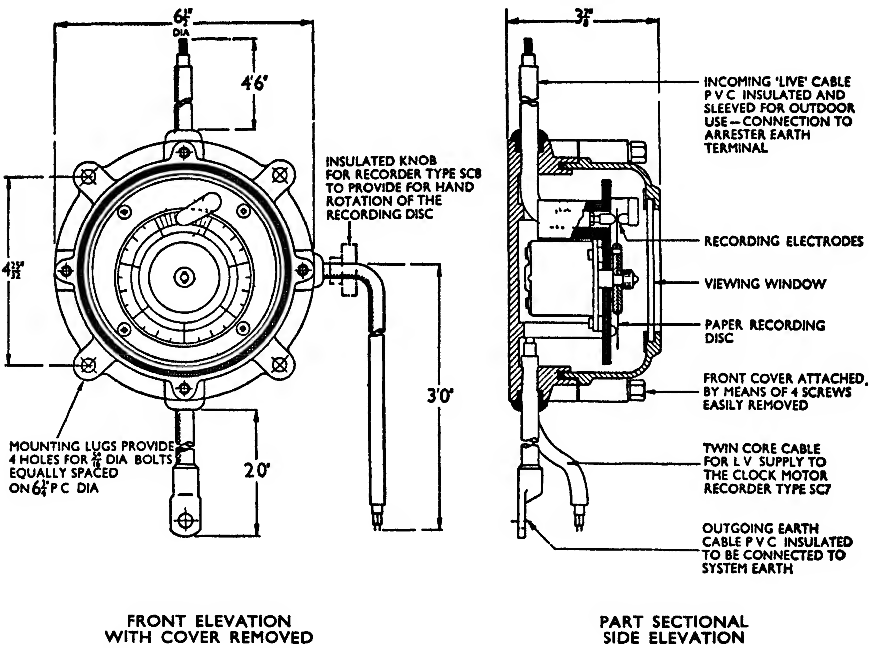


FIG. 21-21.—*Surge counter with recording paper disc.* (*EMP Electric Ltd.*)

APPLICATION OF SURGE DIVERTERS

When considering the application of surge diverters, it is necessary to have a full knowledge of the impulse voltage characteristics of the apparatus to be protected and the protective characteristics of the surge diverter.

For higher voltage systems, the use of apparatus of a high insulation level which has been impulse tested is now practically standard practice. This is costly if applied at lower voltages, and the use of diverters can provide an economical alternative method of protection. As indicated, however, co-ordination of insulation levels is very necessary as obviously that of the apparatus must be above that of the breakdown value of the protective device.

Where and how to install diverters is also important. The many varying conditions and systems which occur in practice cannot be covered in the short space of the present chapter and the subject is one which demands the services of specialist engineers to advise on a particular network the points at which diverters should be placed to give protection against internal or external overvoltage. An appendix in B.S.2914 gives a useful outline and guidance. To obtain advice however, it is essential that the fullest data be given concerning the system, particularly that concerning the neutral of the system and how it is earthed, or alternatively, whether or not it is insulated. Other information essential to a study is that relating to the insulation level of the apparatus to be protected, altitude of location, details of transmission lines or cables, system data, etc.

As to the actual installation, it is, in general, necessary that diverters be installed as near to the apparatus to be protected as possible in order to minimise the risk of a lightning stroke striking a point between the diverter and the apparatus. It is also necessary that the leads from the line conductors to the diverters, and from the diverters to earth, be short and as straight as possible. In order that the residual voltage on the line should be low, the earth resistance must be maintained low. Inadequate earthing will bring about a reduction in the protective level afforded since the IR value it represents must be added to the diverter protective level incorporated The earthing system for the transmission line, substation and surge diverters should be made common, together with any counterpoise embodied.

BIBLIOGRAPHY

B.S. 2914 Surge Diverters.

B.S. 923 Impulse Voltage Testing.

The J. & P. Transformer Book. S. Austen Stigant, M. Morgan Lacey and A. C. Franklin (Johnson & Phillips Ltd.).

"H.V. Lightning Arrestors," K. Dannenberg "Electrical Review," Jan. 13th, 1950.

"The Design and Performance of Surge Diverters for the Protection of Alternating Current Systems," T. F. Monahan, "Journal I.E.E.," Part II, No. 63 June 1951.

"The Measurement of Lightning Voltages and Currents in South Africa and Nigeria," 1935-1937 F. R. Perry, M.Sc. "Journal I.E.E.," Vol 88, Part II, No. 2. 1941.

"Proposed Basic Impulse Insulation Levels for High Voltage Systems," J. E. Cleue, J. R. Meador, W. J. Rudge & A. N. Powell, "Electrical Engineering." (Journal of the American I.E.E.) January 1951 Page 61.

"The Design, Specification and Performance of High Voltage Surge Diverters," H. F. Jones & C. J. O. Garrard, "Journal I.E.E." part II, No. 57, June, 1950.

"Valve Type Surge Diverters" B. C. Hicks, "Electrical Supervisor," October, 1959.

"Insulation Co-ordination in High-Voltage Stations," S. E. Newman and A. R. Parish. "The English Electric Journal," Sept. 1953.

APPENDIX A

MAINTENANCE AND INSPECTION

APPENDIX A

MAINTENANCE AND INSPECTION

THE static nature of electrical switchgear is in some respects, a disadvantage because, unlike rotating machinery, it does not appear to be needful of any maintenance or inspection. Attention to this problem has been focussed on these matters in C.P. 1008, "A Code of Practice for the Maintenance of Switchgear" and C.P. 1009 "Maintenance of Insulating Oil" and all users of switchgear should have these available for study and reference as authoritative documents. Quite a large number of operational difficulties which arise in service can be traced to inadequate maintenance; often to a complete lack of maintenance. A smaller number of major difficulties can be attributed to the same cause although to establish this is always difficult because the cause is so often destroyed by the event, e.g., an accumulation of dust and damp leading to flashover or worse. There is, then, very good reason why electrical switchgear should receive *regular* and *detailed attention*, and the less real work the gear has to do, the more urgent is the need. The notes which follow will be of assistance in the preparation of a scheme which should be formulated to suit the installation.

Any system of maintenance demands as a first requisite an orderly programme with predetermined intervals between inspections. It demands that a full record be kept of each inspection, the work done or the adjustments made (even to such a detail as an adjustment of a trip setting), the work of adjustments necessary but which cannot be carried out there and then, and, to be orderly, special tools, spares, etc., must be at hand.

Switchrooms should not be used, as they so often are, as storerooms for articles unrelated to the switchgear, and tidiness is a major essential. Too often do operators and maintenance staff leave miscellaneous sundries disposed on or about the gear, e.g., rags, spare compound.

Special instruction books issued by makers of specialised equipment, e.g., protective gear, should be to hand and kept in a suitable receptacle at the site rather than in a central office elsewhere. A useful cupboard for housing spare parts, instruction books, diagrams, etc., is shown in Fig. A-1.

Before any work is carried out suitable measures must be taken to guard against danger. It is the responsibility of the occupier to ensure the safety of those whom he deputes to work on the switchgear and a system must be worked out beforehand which will provide adequate safeguards and will nominate the person who will be responsible for the working of the system. No attempt will be made here to outline such a scheme, because so many variations are possible to suit individual installations. Generally, any scheme should include a permit card authorising the work to be done, the card being issued only by the responsible person previously mentioned. The card should clearly indicate without any possible doubt the points at which it is safe to work, the times when it can be done, the steps taken to

ensure safety, such as earthing, isolation, danger notices, locked-out points, etc., and the nearest live point. It should bear the signature of the responsible

FIG. A-1.—*Substation control room showing spares cabinet on wall. Cabinet also contains drawings and instruction books (Johnson & Phillips Ltd.).*

person and after the work is completed should be cancelled and removed from the possession of those doing the work.

Danger notices should only be put up or removed by the responsible person who will take personal charge of any keys used to lock-out items of equipment. The most careful handling of keys is important as many accidents occur due to the wrong use of these, in particular where access to duplicates is relatively easy and their careless use, often by operatives whose knowledge and experience should indicate special vigilance.

The foregoing may appear stringent for small installations, but it must not be overlooked that the electricity is just as lethal on the simple installation as on the very largest and that 400 volts has caused as many deaths as voltages of a higher order. It must also be borne in mind that on the small installation the available staff may not be so highly trained. The catalogue of electrical accidents issued yearly by the Ministry of Labour is a reminder of the great need for care.

The planning of a system of maintenance can be considerably eased if, in the first place, thought is given to the risks and hazards which can arise. For example, dust and damp are two evils so often found in switchrooms as to indicate that little appreciation exists of the hazards they produce. A thought given to this when constructing the switchroom can relieve the work of the maintenance staff. Moisture is always a potential danger and temperature variations which may occur in a room result in condensation. This, particularly if coupled with dust and dirt may sooner or later lead to trouble. The solution is adequate ventilation and a room kept at an *even* temperature. Dust is often present due to the sweeping of ordinary concrete floors. This can be mitigated by the use of one of the paints available which make such surfaces non-dusting, adding, incidentally, to the appearance of the room.

Other precautions in the original planning which are worthy of thought are:—

(1) Fireproof doors, roofs and ceilings.

(2) Sealing of cable ducts.

(3) Installation of fire-fighting apparatus.

(4) Subdivision of switchgear.

Of the many items which need inspection and maintenance, the circuit-breaker is perhaps most important. On this the general safety of the system depends particularly in the interruption of current under abnormal conditions, such as short-circuit. It will therefore be considered first, followed by other details.

CIRCUIT-BREAKERS.

Under normal operating conditions a periodic check should be made on the following.

(*a*) Check level and condition of the oil. Clean the insulators and occasionally examine the contacts to ensure that good contact is being maintained. Arcing contacts should be watched for burning; operating mechanisms should be checked and lubricated.

(*b*) Check the tripping of the breaker through the devices which will have to function on fault or overload, e.g., direct acting trip coils or relays. In the case of relays, operate these manually, e.g., by turning the disc.

(*c*) Check indicating devices, such as mechanical on and off indicators as an incorrect indication may at some time lead to a fatal accident.

(*d*) Check auxiliary switches for cleanliness and contact making.

(*e*) Check all nuts and bolts for tightness, particularly in heavy current installations.

After a circuit-breaker has operated under fault conditions, it should be examined as soon as possible thereafter.

This is important, as while it is accepted that after such an operation the circuit-breaker should be capable of being closed and of making, breaking and carrying its *normal* current, its breaking capacity for a subsequent fault

may be impaired. It is obvious that restoration to its original condition is paramount and the following attention is essential.

(*a*) Examine the oil and if badly discoloured change or recondition. If in good condition, check level to see that this has not fallen by an amount likely to impair future operation. Oil in good condition should withstand 30 kV for one minute, in a standard oil testing cup with 4 mm, plus or minus 0·02 mm, between electrodes.

(*b*) Tank should be lowered and all contacts examined. Arcing contacts must be replaced, or beads of fused metal removed and pitted surfaces cleaned up with a smooth file. Care should be taken to prevent filings falling into the tank, or if they do be sure they are removed before putting back into service.

(*c*) Inspect insulation for possible damage. Carefully clean the surfaces to remove deposits of carbon. Similarly, arc-control devices must be cleaned of carbon. In some designs, replacement of arc-splitting plates is necessary if these have become charred. When cleaning insulators, use a fabric which will not deposit loose fibres. Synthetic resin-bonded paper insulator surfaces may be scratched, and after removing any roughness with fine sand paper, they should be given two coats of special varnish to the suppliers recommendation.

(*d*) Check closing and tripping mechanisms.

(*e*) Make a final inspection to ensure that no tools have been left in the tank, or elsewhere about the breaker, that the tank linings and barriers are in position and secure, and that the tank gasket is in good condition.

CONTACTS

In any switchgear installation there are a variety of contacts other than those in the circuit-breaker. Upon the efficiency of these much depends.

A first essential is that all contact surfaces shall be kept clean and that effective pressure be maintained. Any dirt or oxide on the surface causes high resistance and is the beginning of overheating. A common cause of contact trouble is the softening of backing springs due to temperature.

The formation of oxide on contacts must be particularly looked for as this can become really serious and a vicious circle is possible—oxide—high-temperature—more oxide—higher-temperature, and so on.

Sliding contact surfaces should be kept smooth. The effectiveness of the contact however is dependent on pressure. The old method of checking with an 0·002 in. feeler is not a reliable guide as it is unlikely when two plane surfaces are brought together that they will be in contact all over and while a feeler test may prove that the edges are in contact there may be a measurable gap at points where the feeler cannot be applied.

Contacts on auxiliary switches, control switches, etc., are usually of a simple type but on them depends the correct functioning of many other items of equipment, not the least of which is protective gear. These contacts must be clean, as a small particle of grit may be sufficient to keep them apart.

The bolted type of contact, as where connections join busbars, or breaker stems, or where wiring is connected to instruments or relays, depends on the tightness of the nuts. The habit which nuts have of coming loose is well-known, and happens in spite of all precautions, and it is important to check for tightness at regular intervals. If for any reason a bolted joint is broken down, the surface should be cleaned, smeared with vaseline or contact oil and then scratch brushed before remaking.

OPERATING MECHANISMS.

The intelligent application of a small quantity of lubricant is an essential to satisfactory operation. A "small quantity" is emphasised because excess oil or grease finds its way to other parts, e.g., trip coil plungers, and effectively stops those parts from operating as intended, and if there is dust about, this will collect on any excess lubricant. It is recommended that maintenance on operating mechanisms should include inspection for this possibility.

The correct lubricant to apply to any mechanism or part of it must depend on the design and the guidance of the maker should be sought. In some cases, makers send out mechanisms sprayed with a rust-resisting compound which is also slightly lubricating. This compound should *not* be removed.

During maintenance, old oil or grease with the dust it has probably collected, should be cleaned away before applying new oil or grease.

Check nuts for tightness, and pins and split pins for correctness of fitting.

CONTROL PANELS AND WIRING.

Few control panels are really dust tight. Clearances between contacts and terminal stems on control and instrument switches, terminal blocks and lamp terminals, are relatively small and dust can accumulate between them to an extent that even the low potential which exists between adjacent stems may cause breakdown, particularly on flat horizontal surfaces. This type of apparatus can be kept clean by the use of bellows or better still, the vacuum cleaner.

It is vitally important to check indicating lamps as on these a correct knowledge of circuit conditions must depend. This is particularly the case where a single lamp is used may burn out or suffer mechanical damage. Wiring on control panels should be checked for insulation and continuity at intervals of say once a year. Earth connections should also be checked for continuity.

Fuses, too, are all important. Those of the cartridge type can be checked by keeping a record of resistance. Wire fuses should be examined visually.

When replacing cartridge type fuses or rewiring other types, always use the correct fuse-link rating or the correct gauge of wire.

PROTECTIVE GEAR.

Protective gear is installed for the purpose of disconnecting the apparatus from the electrical system when that apparatus or its connecting conductors become faulty. By this means extensive damage involving a major shut-down may be avoided. It is of primary importance therefore that protective

gear be kept in sound condition *at all times*, and to this end a regular check on its functions is essential.

It is particularly important that a check be made after any maintenance operation which may have necessitated disturbing certain connections.

Many protective systems in use to-day are of a special type (see Chapter XV) and with these, the makers usually issue instruction booklets to cover both the operation, testing and maintenance. In the simpler forms of protective gear the most satisfactory test is to simulate a fault by passing current (preferably by primary injection) through the windings of the protective transformers causing the gear to function as intended.

Relays must be kept clean, the contacts being checked to make sure that contact does actually occur.

Settings should be checked and connections to relays should be tight under the nuts on the stems. Corrosion of connections should be looked for particularly in damp situations, where corrosion occurs mainly on d.c. elements, e.g., trip circuits.

BATTERIES.

Usually employed for the closing operation of the circuit-breaker or for trip coils, indicating devices, etc., it is essential that batteries be maintained in sound condition.

This can usually be checked from the specific gravity of the electrolyte, which should be maintained at its correct level. Connections should be tight and corrosion checked by smearing the terminals with petroleum jelly.

Trip batteries are usually of the nickel iron type and require little attention. They are supplied in cabinets which accommodate trickle charging equipment, test switches and instruments.

INSTALLATION ON SITE.

Owing to the many variations in design of electrical switchgear, no fixed rules can be set down to cover the essentials of satisfactory installation but on this will depend the correct functioning of the gear. In many cases, the makers issue individual instructions for use when their own erection staff are not called upon to undertake the work.

A chief essential is that of having a true and level foundation, and the careful lining up of the gear on this foundation prior to final joining up, using where necessary shims to adjust for small inaccuracies. It is vitally important that, in types of gear where there is a fixed housing into which a moving carriage has to enter, the housing be plumb. In types of gear where compounding has to be done on site, e.g., in compound-filled switchgear at joints between adjacent units, care should be taken to follow closely the manufacturers' instructions.

SITE TESTING.

It is often the case that switchgear is installed in a switchroom some time before it is commissioned. It may be that the room is damp, may not even have a roof, and that other contractors are still working in the room. Such conditions warrant a careful examination of the gear before commissioning, ensuring that every detail is dry and clean, that working parts are properly lubricated, etc.

Wedges which may have been used to prevent damage in transit should be removed. If any special precautions must be taken, these are usually indicated by tags tied to the gear and it is recommended that these be removed by a responsible person only and *not*, as is so often the case, by a stores receiving clerk before the apparatus reaches the final site. Such instructions usually cover the need to fill voltage transformers with oil, the removal of protective shrouds from synthetic resin-bonded paper bushings, and the removal of paper wedges from protective relays.

Insulation resistance tests should be carried out on both primary and secondary circuits using a 1 000 volt instrument. If damp is present unsatisfactory readings may be obtained and in this case, all insulating surfaces should by carefully wiped with a warm dry cloth. In the extreme case it may be necessary to dry out the gear by other means and if this is necessary radiators or heaters should be placed so that there is no danger of blistering the surfaces of the insulation.

Voltage tests should subject all main connections to twice the service voltage plus 2 000 volts for one minute, at a frequency of 50 cycles per second. If tests of a longer duration are required, then the voltage should be reduced in line with the following:—

Duration of test	Percentage of standard test voltage
Minutes	
1	100
2	83·5
3	75·0
4	70·0
5	66·6
10	60·0
15	57·7

It often occurs that d.c. voltage tests have to be applied, owing to the length of connected cable. The latter would demand such a high charging current as to make the size of a testing transformer for a.c. very large and unwieldy. The correct d.c. voltage to apply is $\sqrt{2}$ times the r.m.s. value of the a.c. test voltage. In some cases, the locations of the current transformers will be such as to bring them within the range of d.c. tests applied to cables and when this occurs consideration must be given to the advisability or otherwise of disconnecting the transformers, which may not be capable of withstanding the d.c. voltage. In all cases of d.c. testing the manufacturers agreement should be obtained, notably because the usual time of application to cables is 15 minutes.

Repeated voltage testing is generally deprecated as while a breakdown may not occur immediately, the insulation is stressed and repeated stressing may in time be the cause of breakdown. In any event, it is well to remember that the gear has already been voltage tested at the makers' works and in

many cases further high-voltage tests might be dispensed with without danger. It may be wise however to voltage test the busbars on compound-filled gear on site as these are never completely finished at the joints at the works.

Generators, transformers and feeders must be phased out. In the case of generators, the phase rotation of the generator must be checked against the system it is to serve. For this purpose a phase-rotation indicator is useful but other methods include checking against an induction motor of known rotation or by lamps across the secondaries of suitable voltage transformers. In the case of transformers where these operate in parallel, not only must a rotation check by made, but they must be phased out on each phase. All feeders must be similarly phased out, verifying each phase in turn and simultaneously proving continuity.

BIBLIOGRAPHY.

C.P.1008. Code of Practice for the Maintenance of Switchgear.

C.P.1009. Maintenance of Insulating Oil.

Electric Power Stations, T. H. Carr (Chapman and Hall).

Protective Gear Handbook, M. Kaufman, (Pitman and Sons).

Switchgear Principles, P. H. G. Crane, (Cleaver-Hume Press Ltd.).

APPENDIX B

REGULATIONS

APPENDIX B

REGULATIONS

In general, switchgear installations in Great Britain must comply with the Factories Acts, the requirements of which are explained in a "Memorandum on the Electricity Regulations". These apply to all power and substations, and the user of electrical switchgear in any form is well repaid by a study of the Memorandum numbered "Form 928", issued by H.M. Stationery Office.

Separate regulation sare issued to cover use in Mines and Quarries and reference is directed to H.M. Stationery Office publication, "Mines and Quarries Form No. 11".

Local regulations may need to be taken into account on any particular installation, and in this case onus is on the prospective purchaser to indicate these at the time of enquiry.

It may be useful here to give a brief extract from the Electricity Regulations insofar as they affect switchgear in particular:

An "Electrical Station" is defined in the Factories Act 1961 as "any premises in which persons are regularly employed in, or in connection with the processes or operations of generating, transforming or converting, or of switching, controlling or otherwise regulating, electrical energy for supply by way of trade or for supply for the purposes of any transport undertaking or other industrial or commercial undertaking or of any public building or public institution, or for supply to streets or other public places, as if the premises were a factory and the employer of any person employed in the premises in or in connection with any such process or operation were the occupier of a factory." The foregoing is extracted from Section 123 of the 1961 Act.

Under the heading of "Definitions" in the Memorandum, a substation is noted as:—

"Any premises, or that part of any premises, in which electrical energy is transformed or converted to or from pressure above medium pressure, except for the purpose of working instruments, relays, or similar auxiliary apparatus; if such premises or part of premises are large enough for a person to enter after the apparatus is in position."

This, it will be seen, excludes certain kiosks, street pillars and the like in that no person can enter with the apparatus in position.

Notwithstanding, such forms of substation may still be subject to certain regulations either under the definition of "Electrical Station" or because they are on premises to which the Acts apply. It is therefore excellent practice to regard a kiosk as being subject to the regulations, and to provide the safeguards applicable.

As to "pressure"†, the following definitions apply:—

" 'Low-pressure' means a pressure in a system normally not exceeding 250 volts where the electrical energy is used.

" 'Medium-pressure' means a pressure in a system normally above 250 volts, but not exceeding 650 volts, where the electrical energy is used.

" 'High-pressure' means a pressure in a system normally above 650 volts but not exceeding 3,000 volts, where the electrical energy is used or supplied.

" 'Extra high-pressure' means a pressure in a system normally exceeding 3 000 volts where the electrical energy is used or supplied."

In the case of alternating current systems the term "pressure" refers to the r.m.s. value.

Certain exemptions are laid down in regard to a number of the regulations, the full intent of which should be studied in the Memorandum referred to. These exemptions mainly concern low-pressure systems, apparatus on the supply side of consumers' terminals, situations where special conditions adequately prevent danger, and processes or apparatus used exclusively for electro-chemical or electro-thermal or testing or research purposes.*

In considering the regulations, it is important to bear in mind that:—

"It shall be the duty of the occupier to comply with these regulations. And it shall be the duty of all agents, workmen and persons employed to conduct their work in accordance with these regulations."

This observation is worthy of particular stress in conjunction with the need for regular switchgear maintenance, dealt with in Appendix A.

It is of importance in that gear originally supplied by a manufacturer to meet all the requirements of safety demanded, may be rendered less safe, or even unsafe, by lack of maintenance or care.

Dealing now with the regulations particularly applying to switchgear, it will be convenient to set these down followed by brief comments which may be of help.

REGULATION 1.

"All apparatus and conductors shall be sufficient in size and power for the work they are called upon to do, and so constructed, installed, protected, worked and maintained as to prevent danger so far as is reasonably practicable."

Applicable to all system pressures, it is noted that here again the word "maintained" occurs. The regulation covers the need for precautions when working on live conductors such as on switchboards. "Sufficient in size and power" means not only for normal conditions but also under conditions of short-circuit as indicated in various chapters in this book.

**Exemption 4 has a proviso which specifically qualifies the conditions under which exemption is granted and these must be noted and complied with.*

† *Voltage*

REGULATION 3.

"Every switch, switch fuse, circuit-breaker and isolating link shall be (*a*) so constructed, placed or protected as to prevent danger; (*b*) so constructed and adjusted as accurately to make and maintain good contact; (*c*) provided with an efficient handle or other means of working, insulated from the system, and so arranged that the hand cannot inadvertently touch live metal; (*d*) so constructed or arranged that it cannot accidentally fall or move into contact when left out of contact."

In the types of switchgear outlined in the present work, the construction is generally such that danger in the manner indicated is avoided. The reference to the need for the maintenance of contacts to give good contact is important in the case of circuit-breakers where fault clearance may result in burning such that good contact is impossible.

The operation of isolating links, if of the single pole, pole operated types, demands a pole of adequate insulating properties and length. When closed, such links should be held closed by safety catch or other means. In the case of ganged isolators, a toggle or other means should hold the isolator in or out, and a definite "on" and "off" indicator should be provided.

Modern circuit-breakers are normally fitted with indicating devices to show open or closed positions.

REGULATION 4.

"Every switch intended for breaking a circuit and every circuit-breaker shall be so constructed that it cannot with proper care be left in partial contact. This applies to each pole of double-pole or multi-pole switches or circuit-breakers. Every switch intended to be used for breaking a circuit and every circuit-breaker shall be so constructed that an arc cannot be accidentally maintained."

The intent of this regulation is such that slow-break isolators must not be used for breaking current. Reference has been made elsewhere to the possibility of drawing a dangerous arc under such conditions. In the case of circuit-breakers, quick-break action is provided independent of the operating handle, thus complying with the regulation.

REGULATION 5.

"Every fuse, and every automatic circuit-breaker used instead thereof, shall be so constructed and arranged as effectively to interrupt the current before it so exceeds the working rate as to involve danger. It shall be of such construction or be so guarded or placed as to prevent danger from overheating, or from arcing or the scattering of hot metal or other substance when it comes into operation. Every fuse shall be either of such construction or so protected by a switch that the fusible metal may be readily renewed without danger."

This regulation is important in many respects. First and foremost it demands apparatus capable of adequately dealing with fault conditions. This has been indicated in Chapters III and IV and methods have been given whereby the fault conditions to be expected can be calculated with reasonable accuracy for the purpose of correct selection.

It is important to note that if, for any reason, fuses rated to allow an initial current rush without "blowing" have to be employed, as for example on a motor starter for direct-on-line switching, then it is possible that cables rated for full-load current will not be protected.

As to the scattering of hot metal and arcing, it demands that an open-type air circuit-breaker shall be placed sufficiently high as to be away from an operator's face. Danger from "other substance" can mean the throwing of hot oil and gases from the vent pipes of oil circuit-breakers and these pipes should therefore be brought out to a point remote from that where an operator should or would normally be.

An important point brought out by the regulation is that of ensuring that instrument fuses and the like should be of high breaking capacity if they are in any part of the circuit where the full value of short-circuit may need to be interrupted by them.

As to main circuit fuses, the many excellent makes now available which comply in all respects with the regulations make the matter one of choice. Care, however, is needed in the selection of fuse-link rating to ensure that the protection intended is really obtained.

REGULATION 7.

"Efficient means, suitably located shall be provided for cutting off all pressure from every part of a system as may be necessary to prevent danger."

The need for maintenance on circuit-breakers has been stressed elsewhere. In the event of it being impossible to shut down completely, as for example at week-ends or night, then isolators to *completely* isolate the breaker are essential, and such links must be so located, with dividing barriers or screens, as to prevent danger to persons working, noting that the busbar side of such isolator can be live.

REGULATION 8.

"Efficient means, suitably located, shall be provided for protecting from excess of current every part of a system, as may be necessary to prevent danger."

Compliance with this regulation depends largely on the efficiency and suitability of the protective gear provided. It must be borne in mind that some time, no matter how small, must elapse while the protective gear functions and the associated interrupting device operates to clear an excess current condition and during this period the current must be carried by busbars, conductors, current transformer primaries, etc. To prevent danger it will be clear that the time period should be as short as possible. The need for circuit interrupting devices to be capable of interrupting the maximum fault current is again emphasised.

REGULATION 14.

"The general arrangement of switchboards shall, so far as reasonably practicable, be such that:—

(*a*) All parts which may have to be adjusted, or handled, are readily accessible.

(*b*) The course of every conductor may where necessary be readily traced.

(*c*) Conductors not arranged for connection to the same system are kept well apart, and can, where necessary, be readily distinguished.

(*d*) All bare conductors are so placed or protected as to prevent danger from accidental short-circuit."

Where there is any quantity of small wiring, and particularly in the case of electrically remote controlled boards, the ends of each wire can with advantage be numbered to correspond with the wiring diagram.

This is important in that in many cases wires of similar colour run in the same direction and from and to points closely adjacent.

In any case, whether the quantity of wiring is great or small, it should be run neatly and not strung from point to point. It should follow as closely as possible the runs shown on the diagram of connections.

Although not specifically mentioned in the regulation, the adequate labelling of instrument and other auxiliary fuses is equally important in tracing out circuits in the manner intended.

Accidental short-circuit, referred to in (*d*), may arise from a number of causes. Fuses or switches, where there is a risk of arcing, may, if placed close to adjacent metal, either in the circuit or not, be one cause. Conductors of opposite polarity or phase must be spaced adequately or where this is impossible, insulation introduced between.

All apparatus required to be handled, e.g. fuses in secondary circuits and operating handles, should be placed at the front of a switchboard.

REGULATION 15.

"Every switchboard having bare conductors normally so exposed that they may be touched, shall, if not located in an area or areas set apart for the purposes thereof, where necessary be suitably fenced or enclosed.

"No person except an authorised person, or a person acting under his immediate supervision, shall for the purpose of carrying out his duties have access to any part of an area so set apart."

As pointed out in Form 928, "a place set apart" means that the place shall not be used for *any* other purpose whatsoever. The regulation is one which the user must study in all its implications in relation to the situation under consideration. If the switchgear manufacturer is to provide any special precautions, these should be stated at the time of enquiry and full particulars of the conditions given.

REGULATION 16.

"All apparatus appertaining to a switchboard and requiring handling, shall so far as practicable be so placed or arranged as to be operated from the working platform of the switchboard, and all measuring

instruments and indicators connected therewith shall, so far as practicable, be so placed as to be observed from the working platform. If such apparatus be worked or observed from any other place, adequate precautions shall be taken to prevent danger."

This clearly precludes the placing of such apparatus as may need to be handled or observed in normal operation at the back of a board.

In particular, instrument and other auxiliary fuses should be renewable at the front, away from any possible danger. See also Regulation 14.

REGULATION 17.

"At the working platform of every switchboard and in every switchboard passage-way, if there be bare conductors exposed or arranged to be exposed when live so that they may be touched, there shall be a *clear* and *unobstructed* passage of ample width and height, with a *firm* and *even* floor. Adequate means of access free from danger, shall be provided for every switchboard passage-way.

"The following provision shall apply to all such switchboard working platforms and passage-ways constructed after January 1st, 1909, unless the bare conductors, whether overhead, or at the sides of the passage-ways, are otherwise adequately protected against danger by divisions or screens or other suitable means:—

(*a*) Those constructed for low-pressure or medium-pressure switchboards shall have a clear height of not less than seven feet, and a clear width measured from bare conductor of not less than three feet.

(*b*) Those constructed for high-pressure and extra high-pressure switchboards, other than operating desks or panels working solely at low-pressure shall have a clear height of not less than eight feet, and a clear width measured from bare conductor of not less than three feet six inches.

(*c*) Bare conductors shall not be exposed on both sides of the switchboard passage-way unless either (1) the clear width of the passage-way is, in the case of low-pressure and medium-pressure, not less than four feet six inches, and in the case of high-pressure and extra high-pressure not less than eight feet, in each case measured between bare conductors, or (2) the conductors on one side are so guarded that they cannot be accidentally touched."

Certain words in the first paragraph of this regulation have been printed in italics (on the author's instructions) because they are deserving of special attention. There is a tendency in some cases to carefully observe the prescribed clearances and then to obstruct the passage-way with loose-lying cable, or even to build, for some reason, a step. Nothing over which a man can stumble should be placed in the passage-way.

"Adequate means of access" is important. A passage-way with access (and escape) at one end only constitutes a danger in that a man working at the remote end may be trapped by fire or other cause. On the other hand, if the passage-way is very wide a second means of escape may be

unnecessary where only limited power is available at the switchboard. An escape door should be provided if the length of the board is particularly great.

In the case of equipments having doors which may be opened to 90°, the leaving of a passage-way of the minimum dimension from bare conductors, may seriously restrict the escape of a person. It is the view of the Factory Department that the clear width of the passage-way behind any switchboard should be that indicated in the appropriate section (*a*), (*b*) or (*c*) measured from the edge of a door opened at 90°, to the wall.

Where circumstances permit, doors which open through 180° are to be preferred, while some saving in space, yet maintaining the requisite passageway, may be obtained by double doors hinged at opposite sides, instead of one wide door.

REGULATION 18.

"In every switchboard for high-pressure or extra high-pressure:—

(*a*) Every high-pressure or extra high-pressure conductor within reach from the working platform or in any switchboard passage-way shall be so placed or protected as adequately to prevent danger.

(*b*) The metal cases of all instruments working at high-pressure or extra high-pressure shall be either earthed or completely enclosed with insulating covers.

(*c*) All metal handles of high-pressure and extra high-pressure switches, and where necessary to prevent danger, all metal gear for working the switches shall be earthed.

(*d*) When any work is done on any switchboard for high pressure or extra high pressure the switchboard shall be made dead unless:—

(1) The section of the switchboard on which the work is done (hereinafter referred to as "the relevant section") is made dead and every other section which is live is either (a) so separated from the relvant section by permanent or removable division or screens as not to be a source of danger to persons working on the relevant section, or (b) in such a position or of such construction as to be as safe as if so separated as aforesaid: or

(2) The switchboard itself is so arranged as to be secure that the work is done without danger without taking any of the precautions aforesaid."

Modern switchboards at high or extra high-pressure rarely, if ever, have conductors at the front and in any accessible position at the operating platform. Open types of switchgear such that are contemplated by (*a*) are very much more common on the Continent and recourse is made to guard rails, etc.

As to (*d*) emphasis has already been laid on the need for dividing screens and a recommendation made for the fitting of these initially rather than later. Fixed dividing screens are preferable to removable and

temporary screens. In designing such screens care is necessary to ensure that circuit-breakers can readily be worked on. It is, however, not so easy to screen busbar isolating devices and one point on these may be alive, thus necessitating a complete shut-down, if work has to be done on such apparatus.

Sectionalising, or duplicate busbars, provide methods for overcoming shut-down but care is needed to see that in giving access to, say, one set of busbars or isolators, the other set of isolators are completely screened. Voltage transformers with self-contained high-tension fuses are often worked on without shutting down the circuit. Such work is that of renewing the fuses and means of isolation is therefore essential. Where the isolators are apart from the transformer they must be in a separate compartment. Very often in modern gear, voltage transformers are of the withdrawable type, incorporating a spring loaded or snap type switch.

If this latter type, when withdrawn, leaves live points exposed, automatic shutters become necessary to cover those points.

In connection with this regulation, reference should also be made to B.S. 162 and its Appendices (C) and (D).

REGULATION 19.

"All parts of generators, motors, transformers, or other similar apparatus, at high-pressure or extra high-pressure, and within reach from any position in which any person employed may require to be, shall be, so far as reasonably practicable, so protected as to prevent danger."

This regulation demands little comment as it is self explanatory.

REGULATION 20.

"Where a high-pressure or extra high-pressure supply is transformed for use at a lower pressure, or energy is transformed up to above low-pressure, suitable provision shall be made to guard against danger by reason of the lower pressure system, becoming accidentally charged above its normal pressure by leakage or contact from the higher pressure system."

In the main this regulation applies solely to transformers and naturally includes instrument or protective gear voltage transformers.

REGULATION 21.

"Where necessary to prevent danger, adequate precautions shall be taken either by earthing or by other suitable means to prevent any metal other than the conductor from becoming electrically charged."

In switchgear practice, this involves earthing of metal frames, switch handles and the like, usually accomplished by the general connection of all metal work to an earth bar, which in turn is connected to the earthing system. The efficiency of the earthing system is closely related to this regulation and this aspect is commented on at length in Form 928.

REGULATION 22.

"Adequate precautions shall be taken to prevent any conductor or apparatus from being accidentally or inadvertently electrically charged when persons are working thereon."

Reference to the accident reports will confirm the importance of this regulation.

The locking-off of circuit-breakers controlling the circuit being worked upon is perhaps the safest method with the added safeguard that the key to the lock should be in the possession of the man actually doing the work, or the supervisor or other responsible officer. The use of isolating switches on *both* sides of feeder oil circuit-breakers, or circuit-breakers on other circuits where parallel feeds may be possible, is also a necessity. Where fuses form part of the circuit on which work is to be performed, the fuses should be removed to a safe place.

REGULATION 23.

"Where necessary adequately to prevent danger, insulating stands, or screens, shall be provided and kept permanently in position, and shall be maintained in sound condition."

This regulation is to advise the use of insulating stands, or rubber mats in places where persons have to handle switchgear and where there is a danger of touching bare conductors and so receive a shock to earth. The use of stands of insufficient width is to be guarded against as a man may have only one foot on the stand and the other on non-insulating flooring, such as iron plates. A width of three feet is recommended as minimum.

REGULATION 24.

"Portable insulating stands, screens, boots, gloves, or other suitable means shall be provided and used when necessary adequately to prevent danger and shall be periodically examined by an authorised person."

This regulation has clearly the same object in view as regulation 23 but allows the use of portable stands, etc., in circumstances where their use is so seldom required as to render permanent devices unnecessary; "other suitable means" is intended to cover insulated spanners, screw-drivers, pliers, etc. The proviso demanding periodical inspection is vitally important, particularly in the case of rubber gloves and insulating boots. Suppliers of such items will generally carry out inspection at *regular* intervals at a nominal charge.

REGULATION 25.

"Adequate working space and means of access, free from danger, shall be provided for all apparatus that has to be worked or attended to by any person."

Safe and adequate space is essential where any person has to work on switchgear.

By safe, it may be meant not only electrically but also physically—as for example means may have to be provided to allow a hand-hold for a man.

REGULATION 26.

"All those parts of premises in which apparatus is placed shall be adequately lighted to prevent danger."

For example, if back access is provided to a cubicle type switchboard, then adequate lighting is necessary to prevent danger. Lights so placed to accomplish this need not be constantly burning and the switch for operating them must be away from the danger area.

REGULATION 27.

"All conductors and apparatus exposed to the weather, wet, corrosion, inflammable surroundings or explosive atmosphere, or used in any process or for any special purpose other than for lighting or power, shall be so constructed or protected, and such special precautions shall be taken as may be necessary adequately to prevent danger in view of such exposure or use."

In other words, special risks mean special precautions, for example the use of flameproof switchgear.

REGULATION 28.

This regulation is not quoted here in full as it bears directly on all electrical equipment and defines the law regarding *authorised* persons permitted to work where technical knowledge or experience is essential to prevent danger.

The comments given in the foregoing have, of necessity, been considerably abbreviated. Those in the Memorandum (Form 928), however, are extensive, giving a wealth of helpful information, a study of which must be of value not only to users but to switchgear engineers, designers and draughtsmen.

In addition, three appendices in the Memorandum provide further information on (a) low and medium voltage switchboards, (b) the overhead line regulations and (c) the performance of apparatus under short-circuit conditions, the latter being not dissimilar to that given in Chapter III of this book.

APPENDIX C

DATA—TABLES—DIAGRAMS

APPENDIX C.

DATA—TABLES—DIAGRAMS

THE data and tables included in this Appendix are given for convenient reference. It has been selected as being appropriate to the subject matter of the book and much of it has appeared elsewhere. Where necessary acknowledgment to the source is given in parenthesis.

PROPERTIES OF COPPER (Copper Development Association)

0·1 per cent proof stress (Hard Drawn) ..	15·24 tons per sq. in.
,, ,, ,, ,, ,, (Annealed)	4 tons per sq. in.
Ultimate tensile strength (Hard Drawn) ..	20–30 tons per sq. in.
,, ,, ,, (Annealed)	14–17 tons per sq. in.
Electrical resistivity, annealed, based on I.E.C. Standard per cm. per sq. cm. section, microhms	1·724 1 at 20°C.
,, ,, ,, ,, ,, ,, ,,	1·693 9 at 60°F.
Temperature co-efficient of linear expansion ..	0·000 017 per °C.
,, ,, ,, ,, ,, ..	0·000 009 44 per °F.
Thermal conductivity (Calories/sec/sq. cm/cm/°C.)	0·92
Modulus of elasticity (Hard Drawn)	18.10^6 lb/sq. in.

APPROXIMATE WEIGHT OF COPPER CONDUCTORS (Copper Development Association)

Conductors of uniform cross sectional area:—

$$W=3{\cdot}854\,A$$

Conductor, solid rod:—

$$W=3{\cdot}025\,d^2$$

where W = Weight per foot in pounds
A = cross-sectional area in sq. in.
d = diameter in inches

PROPERTIES OF ALUMINIUM AND ALUMINIUM ALLOY (Alcan Industries Ltd.)

B.S. 2898 : 1957	E I E	E 91 E
Minimum 0·1 per cent proof stress	2 ton/sq. in.	10·5 ton/sq. in.
Minimum ultimate tensile strength	4 ton/sq. in.	13 ton/sq. in.
Electrical resistivity (max.) at 20°C. per cm. per sq. cm. section, microhms	2·873	3·133
Temperature co-efficient of linear expansion (20°C.–200°C.) ..	0·000 023 per °C.	0·000 023 per °C.
Thermal conductivity (Calories/sec/sq. cm/cm/°C.) ..	0·53	0·43
Modulus of elasticity	10.10^6 lb/sq. in.	$9{\cdot}5.10^6$ lb/sq. in.

The figures given above relate to the products of Alcan Industries Ltd. *viz.* Noral CISM (EIE) and Noral D 50 SWP (E 91 E) respectively.

TABLE OF DIELECTRIC CONSTANTS AND ELECTRIC STRENGTHS ("CALCULATION AND DESIGN OF ELECTRICAL APPARATUS")

Insulating material	Dielectric constant		Electric strength volts per mil.	
	Range†	Typical or mean value	Range†	Typical or mean value
Air*	1·0	1·0	69– 79	76
Bakelite	3·6–8·8	5·0	560	560
Bakelite mouldings ..	4·5–7·0	5·7	200– 560	380
Compound semi-solid ..	2·5–3·0	2·8	450– 600	500
Compound semi-fluid ..	2·3–2·6	2·4	300– 400	350
Oil, transformer	2·2–2·5	2·4	250	250
Paper, dry	1·7–2·6	2·4	200– 350	275
Paper, oiled	2·6–3·8	3·5	500– 1 500	550
Paper, synthetic resin-bonded	5·0–5·6	5·2	400– 1 500	750
Porcelain	4·4–6·8	4·8	220– 300	240
Rubber, pure	1·8–2·6	2·3	100– 250	175
Rubber, vulcanised	2·6–2·9	2·7	300– 700	500
Rubber, hard	3·0	3·0	750– 1 500	1 120
Shellac	2·7–3·8	3·2	400– 580	500
Slate	6·0–7·0	6·8	5– 10	6

**At about 760 m/m. pressure. Other gases have a dielectric constant within 1 per cent of unity.*
†Variation due to classes of insulation comprising families of substances with non-identical characteristics and due to the fact that electric strength usually decreases considerably with thickness.

MINIMUM BENDING RADII FOR LEAD SHEATHED AND CORRUGATED ALUMINIUM SHEATHED POWER CABLES

1	2	3	4	5	6	7
Working voltage kV.	Type of cable	Bending radius in terms of D (See Col. 7)				Diameter measured (D)
		Cable laid direct	Cable drawn into ducts	Adjacent to joints and terminals		
				Without former	With former	
Up to and including 11 kV.	All types	12D	12D	10D	8D	Overall
22 kV (earthed neutral)	All types	15D	25D	15D	12D	Overall
	Individual cores of S.L. cable	—	—	15D	12D	Over sheathed core
33 kV.	Single core	30D	35D	20D	15D	Overall
	3-core screened and S.L.	20D	30D	15D	12D	Overall
	Individual cores of S.L. cable	—	—	20D	15D	Over sheathed core

MINIMUM BENDING RADII FOR ALUMINIUM SHEATHED CABLES EXCLUDING CORRUGATED ALUMINIUM SHEATHED CABLES

1	2	3	4	5	6	7
Working voltage kV.	Type of cable	Bending radius in terms of D (See Col. 7)				Diameter measured (D)
		Cable laid direct	Cable drawn into ducts	Adjacent to joints and terminals		
				Without former	With former	
Up to and including 11 kV.	*All types* Up to and including 1·25 in.	12D	15D	12D	10D	Over sheath
	Over 1·25 in. up to 2 in.	15D	18D	15D	12D	Over sheath
	Over 2 in.	18D	25D	18D	15D	Over sheath
22 kV. (earthed neutral)	*All types* Up to and including 2 in.	15D	25D	15D	12D	Over sheath
	Over 2 in.	18D	25D	18D	15D	Over sheath
	Individual cores of S.A. cable	—	—	15D	12D	Over sheathed core
33 kV.	Single core	30D	35D	20D	15D	Overall
	3 core screened and S.A.	20D	30D	18D	15D	Overall
	Individual cores of S.A. cable	—	—	20D	15D	Over sheathed core

P.V.C INSULATED AND SHEATHED ARMOURED CABLES

Minimum bending radius = 8 times the overall diameter.

For cables other than those given above please see I.E.E. Regs. 13th edition and 1961 Amendments.

Note: Unarmoured p.v.c insulated twin and multicore cables with shaped conductors should have a minimum bending radius of 8 *times the outside diameter.*

STANDARD PERCENTAGE IMPEDANCES FOR 50 C/S, THREE PHASE TRANSFORMERS. CONNECTIONS, H.V. OR L.V., DELTA OR STAR

kVA	H.V. WINDING (KV.)										
	3·3	6·6	11	15	22	33	44	55	66	88	110
5	4·75	4·75	4·75	5·5	5·5	6·0					
7·5	,,	,,	,,	5·25	5·25	5·25					
10 to 15	,,	,,	,,	4·75	4·75	4·75					
20 to 40	4·5	4·5	4·5	4·5	4·5	4·5					
50 to 75	,,	,,	,,	,,	,,	,,	5·0	5·5			
100 to 150	4·75	4·75	4·75	5·0	5·0	5·0	5·5	,,	5·5		
200	,,	,,	,,	,,	,,	,,	,,	,,	,,	6·0	
250 to 400	,,	,,	,,	,,	,,	,,	,,	,,	,,	,,	6·5
500 to 1 000	,,	,,	,,	,,	,,	,,	,,	6·0	6·0	6·5	7·0
1 250		5·0	5·0	5·5	5·5	5·5	6·0	6·5	6·5	,,	,,
1 500		5·5	5·5	6·0	6·0	6·0	6·5	7·0	7·0	7·0	7·5
2 000 to 2 500		6·0	6·0	,,	,,	,,	,,	,,	,,	,,	,,
3 000 to 5 000			,,	6·5	7·0	7·0	7·0	7·5	7·5	8·0	8·0
6 000			7·0	7·0	7·5	7·5	7·5	8·0	8·0	8·5	8·5
7 500			,,	7·5	8·0	8·0	8·0	8·5	8·5	9·0	9·0
10 000					9·0	9·0	9·0	9·0	9·0		
12 500 to 30 000					10·0	10·0	10·0	10·0	10·0		

Note: The above values apply to power transformers with standard ratios, and can be modified if required.

RESISTANCE, REACTANCE AND IMPEDANCE OF MULTICORE COPPER AND ALUMINIUM CONDUCTOR, PAPER INSULATED CABLES

The values given are per 1 000 yds. for circular and sector conductor multicore cables for standard line voltages of 1 100 to 33 000 volts and for a frequency of 50 c/s, manufactured in accordance with B.S. 480 : 1954. The temperature basis is 20°C. (68°F.). Figures given are based on nominal dimensions.

Nominal area of conductor	No. and dia. (in.) of conductor wires	Conductor resistance in ohms per 1 000 yd. at 20°C				Inductance (with allowance for lay) per 1 000 yd.	Reactance (at 50 cycles/sec.) per 1 000 yd.	Impedance per 1 000 yd. at 50 cycles/sec. and 20°C	
		Copper		Aluminium					
		D.C. (single core)	A.C. (multicore) with allowance for lay	D C. (single core)	A.C. (multicore) with allowance for lay			Copper	Aluminium
Sq. in.	No/in.					Millihenries	Ohms	Ohms	Ohms
Up to 1 100 V									
*0·007	7/·036	3·559	30	5 890	6·008	0·292	0·092	3·631	6·009
*0·0145	7/·052	1 705	39	2·823	2·879	0·266	0·083	1·741	2·880
0·0225	7/·064	1·128	19	1·863	1 900	0·228	0·072	1 151	1·902
0·04	19/·052	0·6296	122	1·042	1·063	0·208	0·065	0·646	1·065
0·06	19/·064	0·4155	238	0·6878	0·7016	0·200	0·063	0·429	0·704
0·10	19/·083	0 2470	27	0·4090	0·4175	0 192	0·060	0·260	0·422
0·15	37/·072	0·1687	733	0 2792	0·2855	0 185	0·058	0 183	0·291
0·20	37/·083	0·1270	11	0·2101	0·2153	0 182	0·057	0·143	0·223
0·25	37/·093	0 1011	51	0·1674	0 1720	0·180	0·057	0·119	0·181
0·30	37/·103	0·08243	661	0·1365	0·1407	0·178	0·056	0·103	0·152
0 40	61/·093	0·06133	589	0·1015	0·1056	0·177	0·056	0·086	0·119
0·50	61/ 103	0·05001	502	0·08277	0·08707	0 176	0·055	0·078	0·103
0·60	91/·093	0·04113	671	0·06807	0·07258	0·175	0·055	0·072	0·091
1·75	91/·103	0 03353	991	0·05550	0·06043	0·174	0·055	0·068	0·082
0·00	127/·103	0·02402	151	0 03977	0·04569	0·172	0 054	0·063	0·071
3 300 V									
0·0225	7/·064	1·126	1·149	1·863	1·900	0·251	0·079	1·151	1·092
0·04	19/·052	0·6296	0·6422	1·042	1·063	0·227	0·071	0·646	1·065
0·06	19/·064	0 4155	0·4238	0·6878	0·7016	0 216	0·068	0·429	0·705
0·10	19/·083	0 2470	0·2526	0·4090	0·4175	0·205	0 065	0·261	0·423
0·15	37/·072	0·1687	0·1733	0·2792	0·2855	0·197	0·062	0·184	0·292
0·20	37/·083	0·1270	0 1310	0·2101	0·2152	0 192	0·060	0·144	0·224
0·25	37/·093	0·1011	0·1050	0·1674	0·1719	0 189	0·059	0·121	0·182
0 30	37/·103	0·08243	0·08646	0·1365	0 1407	0·187	0·059	0·104	0·152
0·40	61/·093	0·06133	0·06576	0·1015	0·1055	0·183	0·057	0 087	0 120
0·50	61/·103	0·05001	0·05483	0·08277	0 08692	0·181	0·057	0 079	0·104
6 600 V									
0·0225	7/·064	1·126	1·149	1·863	1·900	0·271	0·085	1·152	1·902
0·04	19/·052	0 6296	0·6422	1·042	1·063	0·243	0·076	0·647	1·065
0·06	19/·064	0·4155	0·4238	0·6878	0·7016	0·231	0·073	0·430	0·705
0·10	19/·083	0·2470	0·2525	0 4090	0·4174	0·218	0·068	0·262	0·423
0·15	37/·072	0·1687	0·1732	0·2792	0·2854	0·207	0·065	0·185	0·293
0·20	37/·083	0·1270	0·1309	0·2101	0·2151	0·201	0·063	0·145	0·224
0·25	37/·093	0·1011	0·1048	0·1674	0·1718	0·198	0·062	0·122	0·183
0·30	37/·103	0·08243	0·08631	0·1365	0·1405	0·194	0·061	0·106	0·153
0·40	61/·093	0·06133	0·06546	0·1015	0·1054	0·190	0·060	0·089	0·121
0·50	61/·103	0·05001	0·05471	0·08277	0·08681	0·187	0·059	0·080	0·105

* *Circular conductors*

Nominal area of con-ductor	No. and dia. (in.) of conductor wires	Conductor resistance in ohms per 1 000 yd. at 20°C: Copper D.C. (single core)	Copper A.C. (multicore) with allowance for lay	Aluminium D.C. (single core)	Aluminium A.C. (multicore) with allowance for lay	Inductance (with allowance for lay) per 1 000 yd.	Reactance (at 50 cycles/sec.) per 1 000 yd.	Impedance per 1 000 yd. at 50 cycles/sec. and 20°C: Copper	Impedance: Aluminium
Sq. in.	No/in.					Millihenries	Ohms	Ohms	Ohms
11 000 V (Belted)									
*0·0225	7/·064	1·126	1·149	1·863	1·900	0·331	0·104	1·154	1·903
0·04	19/·052	0·6296	0·6422	1·042	1·063	0·266	0·083	0·648	1·066
0·06	19/·064	0·4155	0·4238	0·6878	0·7016	0·251	0·079	0·431	0·706
0·10	19/·083	0·2470	0·2525	0·4090	0·4174	0·234	0·074	0·263	0·424
0·15	37/·072	0·1687	0·1731	0·2792	0·2853	0·222	0·070	0·187	0·294
0·20	37/·083	0·1270	0·1307	0·2101	0·2151	0·215	0·067	0·147	0·225
0·25	37/·093	0·1011	0·1047	0·1674	0·1717	0·210	0·066	0·124	0·183
0·30	37/·103	0·08243	0·08614	0·1365	0·1405	0·205	0·065	0·108	0·155
0·40	61/ 093	0·06133	0·06538	0 1015	0·1053	0·199	0·063	0·091	0·123
0·50	61/·103	0·05001	0 05445	0·08277	0·08665	0·195	0·061	0·082	0·107
11 000 V (Screened) Earthed neutral									
*0·0225	7/·064	1·126	1·149	1·863	1 900	0·356	0·112	1·154	1·903
0·04	19/·052	0·6296	0·6422	1·042	1·063	0·285	0·090	0·648	1·067
0·06	19/ 064	0·4155	0·4238	0·6878	0·7016	0·268	0·084	0 432	0·707
0·10	19/·083	0·2470	0·2524	0·4090	0·4174	0·249	0·078	0·264	0·425
0·15	37/·072	0 1687	0 1730	0·2792	0·2853	0·235	0·074	0·183	0·295
0·20	37/·083	0·1270	0 1307	0 2101	0·2150	0 227	0·071	0·149	0·227
0·25	37/·093	0·1011	0 1046	0·1674	0·1717	0 221	0·069	0·126	0·185
0·30	37/·103	0·08243	0·08601	0·1365	0·1404	0·216	0·068	0·110	0·156
0 40	61/ 093	0·06133	0 06521	0·1015	0·1052	0·209	0·066	0·092	0·124
0·50	61/·103	0·05001	0 05425	0·08277	0·08653	0·204	0 064	0·084	0·108
11 000 V (Screened) Unearthed neutral									
*0 0225	7/·064	1·126	1·149	1·863	1·900	0 395	0·124	1·155	1·904
0·04	19/·052	0·6296	0·6422	1 042	1·063	0 317	0·099	0·650	1·068
0·06	19/·064	0·4155	0·4238	0·6878	0·7016	0·297	0·093	0·435	0·708
0·10	19/·083	0·2470	0·2524	0·4090	0 4172	0 274	0·086	0 267	0·426
0·15	37/·072	0·1687	0·1729	0·2792	0·2852	0·257	0·081	0·191	0·296
0·20	37/ 083	0 1270	0 1305	0·2101	0·2149	0·247	0·078	0·152	0·229
0·25	37/·093	0 1011	0·1044	0 1674	0·1715	0·240	0·075	0·129	0·187
0·30	37/·103	0·08243	0·08581	0·1365	0·1403	0·233	0·073	0·113	0·158
0·40	61/·093	0·06133	0·06495	0 1015	0·1050	0·224	0·070	0·096	0·127
0·50	61/·103	0·05001	0·05395	0·08277	0·08633	0·219	0·069	0·087	0·110
22 000 V (Belted)									
0·04	19/ 052	0·6296	0·6422	1·042	1·063	0·309	0·097	0·650	1·067
0·06	19/·064	0·4155	0·4238	0·6878	0·7016	0·289	0·091	0·434	0·708
0·10	19/·083	0·2470	0·2524	0·4090	0·4172	0·268	0·084	0·266	0·426
0·15	37/·072	0·1687	0·1729	0·2792	0·2853	0·251	0·079	0·190	0·296
0·20	37/·083	0·1270	0·1306	0·2101	0·2150	0·242	0·076	0·151	0·228
0·25	37/·093	0·1011	0·1045	0·1674	0·1716	0·235	0·074	0·128	0·187
0·30	37/·103	0 03243	0·08589	0·1365	0·1403	0·229	0·072	0·112	0·158

**Circular conductors*

Nominal area of con-ductor	No. and dia. (in.) of conductor wires	Conductor resistance in ohms per 1 000 yd. at 20°C: Copper D.C. (single core)	Copper A.C. (multicore) with allowance for lay	Aluminium D.C. (single core)	Aluminium A.C. (multicore) with allowance for lay	Inductance (with allowance for lay) per 1 000 yd.	Reactance (at 50 cycles/sec.) per 1 000 yd.	Impedance per 1 000 yd. at 50 cycles/sec. and 20°C: Copper	Alumi-nium
Sq. in.	No/in.					Millihenries	Ohms	Ohms	Ohms
22 000 V (Screened) Earthed neutral									
0·04	19/·052	0·6296	0·6422	1·042	1·063	0·341	0·107	0·651	1·069
0·06	19/·064	0·4155	0·4238	0·6878	0·7016	0·319	0·100	0·436	0·709
0·10	19/·083	0·2470	0·2523	0·4090	0·4172	0·294	0·092	0·269	0·427
0·15	37/·072	0·1687	0·1729	0·2792	0·2852	0·275	0·086	0·193	0·298
0·20	37/·083	0·1270	0·1304	0·2101	0·2149	0·263	0·083	0·154	0·230
0·25	37/·093	0·1011	0·1043	0·1674	0·1715	0·255	0·080	0·132	0·189
0·30	37/·103	0·08243	0·08569	0·1365	0·1402	0·248	0·078	0·116	0·160
0·40	61/·093	0·06133	0·06477	0·1015	0·1049	0·238	0·075	0·099	0·129
0·50	61/·103	0·05001	0·05374	0·08277	0·08619	0·231	0·073	0·090	0·113
22 000 V (S.L.) or (S.A.) Earthed neutral									
0·04	19/·052	0·6296	0·6422	1·042	1·063	0·417	0·131	0·655	1·07
0·06	19/·064	0·4155	0·4238	0·6878	0·7016	0·393	0·124	0·442	0·712
0·10	19/·083	0·2470	0·2522	0·4090	0·4172	0·363	0·114	0·277	0·433
0·15	37/·072	0·1687	0·1728	0·2792	0·2852	0·339	0·106	0·203	0·304
0·20	37/·083	0·1270	0·1304	0·2101	0·2149	0·326	0·102	0·166	0·238
0·25	37/·093	0·1011	0·1043	0·1674	0·1714	0·315	0·099	0·144	0·198
0·30	37/·103	0·08243	0·08561	0·1365	0·1401	0·305	0·096	0·129	0·170
0·40	61/·093	0·06133	0·06471	0·1015	0·1048	0·294	0·092	0·113	0·140
0·50	61/·103	0·05001	0·05366	0·08277	0·8614	0·285	0·090	0·105	0·124
33 000 V (Screened) Earthed neutral									
0·10	19/·083	0·2470	0·2522	0·4090	0·4172	0·323	0·101	0·272	0·430
0·15	37/·072	0·1687	0·1728	0·2792	0·2848	0·297	0·093	0·196	0·300
0·20	37/·083	0·1270	0·1304	0·2101	0·2148	0·284	0·089	0·158	0·233
0·25	37/·093	0·1011	0·1043	0·1674	0·1714	0·269	0·084	0·134	0·191
0·30	37/·103	0·08243	0·08557	0·1365	0·1401	0·261	0·082	0·119	0·162
0·40	61/·093	0·06133	0·06461	0·1015	0·1048	0·250	0·078	0·102	0·131
0·50	61/·103	0·05001	0·05355	0·08277	0·08609	0·243	0·076	0·0932	0·115
33 000 V (S.L.) or (S.A.) Earthed neutral									
0·10	19/·083	0·2470	0·2522	0·4090	0·4172	0·397	0·125	0·281	0·436
0·15	37/·072	0·1687	0·1727	0·2792	0·2848	0·366	0·115	0·210	0·307
0·20	37/·083	0·1270	0·1303	0·2101	0·2146	0·349	0·110	0·170	0·241
0·25	37/·093	0·1011	0·1042	0·1674	0·1714	0·332	0·104	0·147	0·201
0·30	37/·103	0·08243	0·08549	0·1365	0·1401	0·325	0·102	0·133	0·173
0·40	61/·093	0·06133	0·06456	0·1015	0·1047	0·309	0·097	0·117	0·143
0·50	61/·103	0·05001	0·05346	0·08277	0·08601	0·302	0·095	0·109	0·128

STANDARD THREE PHASE OIL CIRCUIT-BREAKER RATINGS TO B.S. 936 : 1960

1	2	3	4
Voltage kV	Breaking current kV	Breaking capacity derived from Columns 1 and 2 MVA	Normal currents Amperes
		CIRCUIT-BREAKERS NOT IN FLAMEPROOF ENCLOSURES	
0·415	0·725	0·52	20 30 60
	1·45	1·04	100
	3·60	2·6	100 200
	7·25	5·2	100 200 400
	14·5	10·4	200 400 600 800
	21·6	15·6	200 400 600 800
	36	26	400 600 800 1200 1600
	49·9	31	600 800 1200 1600
			2000 2400 3000
0·6	0·725	0·75	20 30 60
	1·45	1·5	100
	3·6	3·75	100 200
	7·25	7·5	100 200 400
	14·5	15	200 400 600 800
	21·6	22·5	200 400 600 800
	36	37·5	400 600 800 1200 1600
	43·3	45	600 800 1200 1600
			2000 2400 3000
		CIRCUIT-BREAKERS IN FLAMEPROOF ENCLOSURES	
0·415	3·6	2·6	150 250
	7·25	5·2	150 250 400
	14·5	10·4	250 400
0·6	3·6	3·75	150 250
	4·8	5	200
	7·25	7·5	150 250 400
	14·5	15	250 400

Note: It is recognised that a rated normal current less than the lowest standard value given in Column 4 is permissible for circuit-breakers fitted with series-trip coils. All the rated currents (normal and short-circuit) as determined by the trip coil are then assigned by the manufacturer. Circuit-breakers listed as 0·415 kV are suitable for use up to and including 0·44 kV and at any voltage below 0·415 kV. with the appropriate adjustments to the breaking capacity value given in Column 3.
Circuit-breakers listed as 0·6 kV are suitable for use up to and including 0·66 kV and at any voltage below 0·6 kV with the appropriate adjustments to the breaking capacity values given in Column 3.

STANDARD THREE PHASE OIL CIRCUIT-BREAKER RATINGS TO B.S. 116 : 1952

Service voltage kV	Breaking capacity MVA	Symmetrical breaking currents corresponding to Column 2 kA	Normal currents Amperes						
Excluding pole-mounting and flameproof circuit-breakers									
0·415*	15·6	21·6		400	600	800			
	26	36·0		400	600	800	1200	1600	
	31	43·3				800	1200	1600	2000
							2400	3000	
0·6†	22·5	21·6		400	600	800			
	37·5	36·0		400	600	800	1200	1600	
	45	43·3				800	1200	1600	2000
							2400	3000	
3·3	15	2·63	200	400					
	25	4·38	200	400	600				
	50	8·76	200	400	600				
	75	13·1		400	600	800			
	100	17·5		400	600	800			
	150	26·3		400	600	800	1200	1600	2000
	250	43·8				800	1200	1600	2000
6·6	75	6·57		400	600				
	100	8·76		400	600	800			
	150	13·1		400	600	800	1200		
	250	21·9		400		800	1200	1600	
	350	30·6		400		800	1200	1600	
	500	43·8				800	1200	1600	2000
11	75	3·94		400					
	100	5·25		400	600	800			
	150	7·88		400	600	800			
	250	13·1		400		800	1200		
	350	18·4		400		800	1200	1600	
	500	26·3		400		800	1200	1600	2000
	750	39·4				800	1200	1600	2000
22	250	6·57		400					
	350	9·2		400		800			
	500	13·1		400		800	1200		
	750	19·7		400		800	1200		
	1 000	26·3				800	1200	1600	
	1 500	39·4				800	1200	1600	
33	250	4·38		400					
	350	6·13		400					
	500	8·76		400		800			
	750	13·1		400		800	1200		
	1 000	17·5		400		800	1200		
	1 500	26·3		400		800	1200	1600	

**These circuit-breakers are suitable for use at 0·44 kV and at 0·4 kV with the appropriate adjustments to the breaking capacity values given in Column 2.*

†*These circuit-breakers are suitable for use at 0·66 kV with the appropriate adjustments to the breaking capacity values given in Column 2.*

STANDARD THREE PHASE OIL CIRCUIT-BREAKER RATINGS TO B.S. 116 : 1952

Service voltage kV	Breaking capacity MVA	Symmetrical breaking currents corresponding to Column 2 kA	Normal currents Amperes
44	500	6·57	400 800
	750	9·85	400 800 1200
	1 000	13·1	400 800 1200
	1 500	19·7	400 800 1200
66	500	4·38	400
	750	6·57	400 800
	1 000	8·76	400 800
	1 500	13·1	800 1200
	2 500	21·k	800 1200
88	1 000	6·57	600
	1 500	9·85	600
	2 500	16·4	600
110	1 000	5·25	600
	1 500	7·88	600
	2 500	13·1	600
132	1 500	6·57	600
	2 500	10·9	600
	3 500	15·3	800 1200
165	1 500	5·25	600
	2 500	8·76	600
	3 500	12·2	600
220	1 500	3·94	600
	2 500	6·57	600
	3 500	9·2	600
275	3 500	7·38	600
	5 000	10·6	600
	7 500	15·8	800 1200
		POLE-MOUNTING CIRCUIT-BEAKERRS	
6·6	50	4·38	200
11	75	3·94	200
	250	4·38	400

Note: It is recognised that a rated normal current less than the minimum standard value in Column 4 is permissible for circuit-breakers fitted with series trip-coils. All the rated currents (normal and short-circuit) as determined by the trip-coil are then assigned by the manufacturer.

CAPACITORS FOR POWER FACTOR IMPROVEMENT

$$\text{Power factor} = \frac{\text{True power in kilowatts}}{\text{Apparent power in kilo-volt-amperes}} = \cos\phi,$$

where ϕ is the angle by which the load current leads or lags the supply voltage.

ADVANTAGES OF POWER FACTOR IMPROVEMENT

(1) The existing generating plant and the supply network are able to supply additional loads and, therefore, to earn increased revenue.

Extensive replacements or extensions, moreover, may be postponed or even avoided.

(2) The loading and losses in transformers, switchgear, and cables are reduced, with a consequent reduction in the total cost of electricity.

(3) The voltage regulation of the system is improved, and the performance of the plant is further enhanced.

(4) A direct financial saving generally results since tariffs are usually framed to give financial inducement to improve power factor. Where an industrial installation consists mainly of induction motors, the cost of capacitors is generally recovered in less than 18 months.

TARIFFS

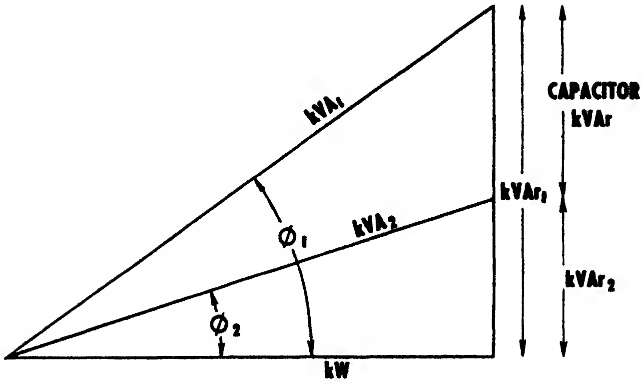
Tariffs under which capacitors will show a definite financial saving on a power bill are those containing:—

(1) A maximum kVA demand charge.

(2) A charge for reactive kVA-hour units.

(3) Those having penalty or bonus/penalty clauses according to the power factor.

REDUCTIONS OF KVA LOADING FOR CONSTANT KW LOADING BY IMPROVEMENT OF POWER FACTOR



Initial Conditions

$$\text{Power Factor} = \text{Cos } \phi_1 = \frac{\text{kW}}{\text{kVA}_1}$$

$$\text{Tan } \phi_1 = \frac{\text{kVAr}_1}{\text{kW}}$$

$$\text{kVAr}_1 = \text{kW} \cdot \text{Tan } \phi_1$$

Improved Conditions

$$\text{Power Factor} = \text{Cos } \phi_2 = \frac{\text{kW}}{\text{kVA}_2}$$

$$\text{Tan } \phi_2 = \frac{\text{kVAr}_2}{\text{kW}}$$

$$\text{kVAr}_2 = \text{kW} \cdot \text{Tan } \phi_2$$

Capacitor kVAr required to improve power factor from

$$\text{Cos } \phi_1 \text{ to Cos } \phi_2 = (\text{kVAr}_1 - \text{kVAr}_2)$$

$$= \text{kW}(\text{Tan } \phi_1 - \text{Tan } \phi_2)$$

This value of capacitor kVAr can be determined either by drawing the vector diagram to scale or by calculation using values from trigonometrical tables.

TABLE OF FACTORS FOR CALCULATING SIZE OF CAPACITOR FOR POWER FACTOR IMPROVEMENT

Initial power factor	Factor for improving power factor to					Initial power factor	Factor for Improving power factor to				
	Unity	0·98	0·95	0·90	0·85		Unity	0·98	0·95	0·90	0·85
0·40	2·291	2·088	1·962	1·807	1·671	0·70	1·020	0·817	0·691	0·536	0·400
0·41	2·225	2·022	1·896	1·741	1·605	0·71	0·992	0·789	0·663	0·508	0·372
0·42	2·161	1·958	1·832	1·677	1·541	0·72	0·964	0·761	0·635	0·480	0·344
0·43	2·100	1·897	1·771	1·616	1·480	0·73	0·936	0·733	0·607	0·452	0·316
0·44	2·041	1·838	1·712	1·557	1·421	0·74	0·909	0·706	0·580	0·425	0·289
0·45	1·984	1·781	1·655	1·500	1·364	0·75	0·882	0·679	0·553	0·398	0·262
0·46	1·930	1·727	1·601	1·446	1·310	0·76	0·855	0·652	0·526	0·371	0·235
0·47	1·878	1·675	1·549	1·394	1·258	0·77	0·829	0·626	0·500	0·345	0·209
0·48	1·828	1·625	1·499	1·344	1·208	0·78	0·802	0·599	0·473	0·318	0·182
0·49	1·779	1·576	1·450	1·295	1·159	0·79	0·776	0·573	0·447	0·292	0·156
0·50	1·732	1·529	1·403	1·248	1·112	0·80	0·750	0·547	0·421	0·266	0·130
0·51	1·686	1·483	1·357	1·202	1·066	0·81	0·724	0·521	0·395	0·240	0·104
0·52	1·643	1·440	1·314	1·159	1·023	0·82	0·698	0·495	0·369	0·214	0·078
0·53	1·600	1·397	1·271	1·116	0·980	0·83	0·672	0·469	0·343	0·188	0·052
0·54	1·559	1·356	1·230	1·075	0·939	0·84	0·646	0·443	0·317	0·162	0·026
0·55	1·519	1·316	1·190	1·035	0·899	0·85	0·620	0·417	0·291	0·136	—
0·56	1·480	1·277	1·151	0·996	0·860	0·86	0·593	0·390	0·264	0·109	—
0·57	1·442	1·239	1·113	0·953	0·822	0·87	0·567	0·364	0·238	0·083	—
0·58	1·405	1·202	1·076	0·921	0·785	0·88	0·540	0·337	0·211	0·056	—
0·59	1·369	1·166	1·040	0·885	0·749	0·89	0·512	0·309	0·183	0·028	—
0·60	1·333	1·130	1·004	0·849	0·713	0·90	0·484	0·281	0·155	—	—
0·61	1·299	1·096	0·970	0·815	0·679	0·91	0·456	0·253	0·127	—	—
0·62	1·265	1·062	0·936	0·781	0·645	0·92	0·426	0·223	0·097	—	—
0·63	1·233	1·030	0·904	0·749	0·613	0·93	0·395	0·192	0·066	—	—
0·64	1·201	0·998	0·872	0·717	0·581	0·94	0·363	0·160	0·034	—	—
0·65	1·169	0·966	0·840	0·685	0·549	0·95	0·329	0·126	—	—	—
0·66	1·138	0·935	0·809	0·654	0·518	0·96	0·292	0·089	—	—	—
0·67	1·108	0·905	0·779	0·624	0·488	0·97	0·251	0·048	—	—	—
0·68	1·078	0·875	0·749	0·594	0·458	0·98	0·203	—	—	—	—
0·69	1·049	0·846	0·720	0·565	0·429	0·99	0·143	—	—	—	—

The above table gives the leading reactive kVA (kVAr) required per kW of load to improve the power factor from the initial value given in Column 1 to the required value shown at the top of Columns 2-6.

Example: Given, 100 kW load to be improved from 0·77 to 0 95 power factor.
Factor from table is 0·500.
∴ Capacitor (kVAr) = 100.0·500 = 50 kVAr.

SUMMARY OF CHARACTERISTICS OF ELECTRIC MOTORS STARTED BY VARIOUS METHODS

Type of starter	Starting torque* %	Starting current* %	Duty rating	Suitable drives	Remarks
Direct-on	100	100	Frequent	Most small machinery	Simple and reliable. Application limited by some supply authorities
Star-delta	33⅓	33⅓	Frequent	Light starting loads, small pumps and fans	Requires 6-terminal motor. Heavy changeover current. Cheap and simple
Auto-transformer	25–60	25–60	Frequent or Intermittent	Large fans, ram pumps and mills	Adjustable starting torque. Smooth start. Expensive
Primary resistance	25–60	50–80	Frequent or Intermittent	Light starting loads, machine tools etc.	Simple. Adjustable but low starting torque with heavy current.
Stator-rotor	100–170	20–42	Frequent or Intermittent	Haulage plant. Any drive with smooth start	For slip-ring motors only. Very smooth start with wide range of torque

**Per cent of direct-on value.*

APPROXIMATE FULL LOAD STATOR CURRENTS FOR THREE PHASE A.C. INDUCTION MOTORS

H.P.	Two phase		Three phase					
	Volts		Volts					
	200	400	200	220	350	400	440	500
1	2·9	1·4	3·4	3·1	2·0	1·7	1·5	1·4
2	5·7	2·9	6·6	6·0	3·8	3·3	3·0	2·6
3	8·4	4·2	9·8	8·9	5·7	4·9	4·5	3·9
4	11·0	5·6	13·0	12·0	7·5	6·5	6·0	5·2
5	14·0	6·8	16·0	14·0	9·1	7·9	7·2	6·3
6	16·0	8·1	19·0	17·0	11·0	9·4	8·5	7·5
7·5	20·0	10·0	24·0	21·0	14·0	12·0	11·0	9·4
8	21·0	11·0	25·0	22·0	15·0	13·0	12·0	9·8
10	26·0	13·0	30·0	27·0	17·0	15·0	14·0	12·0
15	38·0	19·0	44·0	40·0	26·0	22·0	20·0	18·0
20	50·0	25·0	58·0	53·0	34·0	29·0	26·0	23·0
25	62·0	31·0	72·0	66·0	42·0	36·0	33·0	29·0
30	74·0	37·0	86·0	78·0	50·0	43·0	39·0	34·0
40	96·0	48·0	111·0	101·0	64·0	56·0	51·0	45·0
50	118·0	59·0	137·0	124·0	79·0	68·0	62·0	55·0
60	140·0	70·0	162·0	147·0	94·0	81·0	74·0	65·0
75	171·0	86·0	198·0	180·0	114·0	99·0	90·0	79·0
100	228·0	114·0	263·0	239·0	152·0	132·0	120·0	105·0
150	336·0	168·0	388·0	356·0	225·0	194·0	176·0	155·0
200	446·0	223·0	517·0	468·0	299·0	258·0	235·0	207·0

Notes: 1. *Values are in amperes per phase assuming average power factor and efficiency.*
2. *Currents at 550 volts for three phase motors are approximately the same as the H.P.*

TABLE OF CONDUIT SIZES FOR SINGLE CORE CABLES APPROPRIATE TO MOTOR H.P.

	V.I.R. CABLES			
H.P.	Three in conduit		Six in conduit	
	Cable	Conduit	Cable	Conduit
Up to 2	3/·029	⅝"	3/·029	¾" or 1"
3 to 5	3/·036	¾"	3/·036	1"
6	3/·036	¾"	7/·029	1"
8	7/·029	¾"	7/·029	1"
10	7/·029	¾"	7/·036	1¼"
12	7/·036	1"	7/·036	1¼"
15	7/·036	1"	7/·044	1¼"
20	7/·044	1"	7/·052	1½"
25	7/·052	1"	7/·064	1½"
30	7/·064	1¼"	19/·044	2"
35	19/·044	1¼"	19/·052	2"

Note: ***Based on running current per phase***

FUSING GUIDE FOR MEDIUM-VOLTAGE MOTOR STARTING CIRCUITS

In all applications where fuses are used for the protection of motors, it is important to appreciate that the fuse serves solely to protect the motor, the starter itself and the cables against short-circuit. Overload protection, if required, must be provided at the motor starter. It is important, too, to remember that the discrimination afforded by the modern h.r.c. cartridge fuse can only be obtained by a proper selection of the fuse rating. In the case of steady loads the selection of the fuse rating will depend on characteristics entirely different from those of a motor circuit, and these must, if full value of the protection afforded is to be obtained, be taken into full account.

It has been repeatedly stressed that the performance of the h.r.c. fuse can be nullified by haphazard selection of normal rating. Too often is selection made by determining the fuse rating by the maximum rating of the switch or circuit-breaker with which it is associated. This can rarely be described as "selection" and incorrect operation, or lack of operation, can be regularly traced to this method. The following is a good guide to correct selection.

Ratings selected from the table which follows are such that fuses will carry the currents likely to be encountered in normal service but will operate in a minimum of time under fault conditions.

The method of selection is as follows:—

Motor circuits may be divided into three classes of drive. Classes A and B are the most common, and are covered in the table for squirrel cage, slip ring and d.c. motors, and further sub-divided for type of starter. For squirrel cage motors, the standstill current is required; for slip ring and d.c. motors, the full load current. Given the data as outlined above, selection is made by reference to the table overleaf, as the following example indicates.

Squirrel-cage motor.
Type of drive—A.
Starter—direct on line.
Standstill current = 80 amps.
Nearest higher figure Column 1 = 86 amps.
Corresponding fuse rating = 50 amps.

If the motor is started more than ten times per hour or the ambient temperature is 35°C or more the standstill current must be multiplied by the factor 1·1, thus:

Standstill current = 80 amps.
Frequent start factor = 80 . 1·1 = 88 amps
Nearest higher figure Column 1 = 112 amps.
Corresponding fuse rating = 60 amps.

The third class of drive, C, requires special consideration and suitable ratings should be ascertained from the fuse maker. The information required is:—

Type of machinery being driven.
Moment of inertia of moving parts.
Type of motor and starter.
Full-load and standstill currents.
Time to run up to speed.
No. of starts per hour.
Ambient temperature.

Fuse rating	Type of motor and starter					
	Squirrel-cage motors				Slip-ring or direct current motors	
	Direct-to-line starter		Star-delta or auto-transformer starter		Resistance starter	
	(1) A	(2) B	(3) A	(4) B	(5) A	(6) B
	Standstill current not in excess of	Standstill current not in excess of	Standstill current not in excess of	Standstill current not in excess of	F.L. current not in excess of	F.L. current not in excess of
amps	amps	amps	amps	amps	amps	amps
10	17	16·5	23	22·5	4·6	4·5
20	35	33	48	46	9·7	9·1
30	53	50	73	69	14·5	14
40	70	67	97	92	19·5	18·5
50	86	82	119	112	24	22
60	112	103	154	142	31	28
80	164	149	225	205	45	41
100	205	185	280	255	56	51
150	415	370	570	510	114	102
200	600	525	825	725	165	145
250	780	675	1 080	925	215	185
300	950	820	1 310	1 130	265	225
350	1 150	1 020	1 600	1 400	320	280
400	1 350	1 180	1 850	1 620	370	325
450	1 580	1 375	2 200	1 860	435	375
500	1 750	1 470	2 380	2 020	475	405
600	2 100	1 820	2 900	2 500	580	500
700	2 550	2 130	3 500	2 950	700	590
750	2 850	2 400	3 950	3 300	750	665
800	3 100	2 600	4 250	3 550	800	710

A = *Normal industrial drives with starting time not exceeding 12 seconds, e.g. light or medium machine tools, presses, industrial machinery.*

B = *Drives with heavy inertia, starting time not exceeding 30 seconds, e.g. induced and forced draught fans, blowers, centrifuges.*

A FUSING GUIDE FOR H.V. EXPULSION TYPE FUSES ON PAGES 601-622

kVA	Fuse rating, slow-acting elements				Fuse rating, fast-acting elements			
	Transformer protection		Feeder protection		Transformer protection		Feeder protection	
	11 kV	6·6 kV	11 kV	6·6 kV	11 kV	6·6 kV	11 kV	6·6 kV
Minium Ratings Of Fuse Elements For Three Phase Operation								
5	2	3	2	2	3	5	3	3
7·5	2	3	2	2	3	5	3	3
10	3	5	2	2	5	7·5	3	3
15	3	5	2	3	5	10	3	3
20	3	7·5	3	5	7·5	10	3	5
25	5	7·5	3	5	7·5	15	3	5
30	5	7·5	5	5	10	15	3	5
40	7·5	10	5	5	10	20	3	5
50	7·5	15	5	7·5	15	20	5	7·5
75	10	20	7·5	10	15	25	5	10
100	15	20	7·5	15	20	40	7·5	15
150	20	30	10	20	25	50	10	20
200	20	40	15	25	40	—	15	25
250	30	40	20	30	40	—	20	30
300	30	50	25	40	50	—	20	40
400	40	60	30	50	—	—	30	50
500	50	75	40	60	—	—	40	—
750	60	—	50	—	—	—	50	—
1 000	75	—	75	—	—	—	—	—

Minimum Ratings Of Fuse Elements For Single Phase Operation

kVA rating	Fuse rating, slow-acting elements				Fuse rating, fast-acting elements			
	Transformer protection		Feeder protection		Transformer protection		Feeder protection	
	11 kV	6·6 kV	11 kV	6·6 kV	11 kV	6·6 kV	11 kV	6·6 kV
1	2	2	2	2	3	3	3	3
2·5	2	3	2	2	3	5	3	3
5	3	5	2	2	5	7·5	3	3
7·5	3	5	2	3	5	10	3	3
10	5	7·5	2	3	7·5	15	3	3
15	5	10	3	5	10	15	3	5
20	7·5	10	5	7·5	10	20	5	7·5
25	7·5	15	5	10	15	20	5	10
30	7·5	20	5	10	15	25	5	10
40	10	20	5	10	20	30	5	10
50	15	20	7·5	10	20	40	7·5	10
75	20	30	10	15	25	50	10	15
100	20	40	15	20	40	—	15	20
167	30	50	20	30	50	—	20	30
200	40	60	25	40	—	—	25	40
250	40	75	30	50	—	—	30	50
333	50	—	40	75	—	—	40	—
500	75	—	60	—	—	—	—	—
667	—	—	75	—	—	—	—	—

FRACTIONS AND DECIMALS OF AN INCH

Fraction	Decimal	Millimetres	Nearest S.W.G. No.	
			No.	Inch
1/64	0·015625	0·3969	28 27	0·0148 0·0164
1/32	0·03125	0·7937	21	0·032
1/16	0·0625	1·5875	16	0·064
3/32	0·09375	2·3812	13	0·092
1/8	0·125	3·1750	10	0·128
5/32	0·15625	3·9688	8	0·160
3/16	0·1875	4·7625	6	0·192
7/32	0·21875	5·5563	5	0·212
1/4	0·25	6·35	3	0·252
9/32	0·28125	7·1438	2	0·276
5/16	0·3125	7·9375	1	0·300
11/32	0·34375	8·7313	2/0	0·348
3/8	0·375	9·5250	3/0	0·372
13/32	0·40625	10·3188	4/0	0·400
7/16	0·4375	11·1125	5/0	0·432
15/32	0·46875	11·9063	6/0	0·464
1/2	0·5	12·7	7/0	0·5
17/32	0·53125	13·4938		
9/16	0·5625	14·2875		
19/32	0·59375	15·0813		
5/8	0·625	15·875		
21/32	0·65625	16·6688		
11/16	0·6875	17·4625		
23/32	0·71875	18·2563		
3/4	0·75	19·05		
25/32	0·78125	19·8438		
13/16	0·8125	20·6375		
27/32	0·84375	21·4313		
7/8	0·875	22·225		
29/32	0·90625	23·0188		
15/16	0·9375	23·8125		
31/32	0·96875	24·6063		

TABLES OF LOGARITHMS AND ANTILOGARITHMS

Logarithms

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21	25	29	33	37
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17	21	24	28	31
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
18	2553	2577	2601	2615	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7

Logarithms

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
55	7404	7412	7419	7427	7435	7443	7541	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8459	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9639	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9753	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4

To convert common to hyperbolic logs, multiply by 2·3026.

Antilogarithms

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
·00	1000	1002	1005	1007	1009	1012	1014	1016	1019	1021	0	0	1	1	1	1	2	2	2
·01	1012	1026	1028	1030	1033	1035	1038	1040	1042	1045	0	0	1	1	1	1	2	2	2
·02	1047	1050	1052	1054	1057	1059	1062	1064	1067	1069	0	0	1	1	1	1	2	2	2
·03	1072	1074	1076	1079	1081	1084	1086	1089	1091	1094	0	0	1	1	1	1	2	2	2
·04	1096	1099	1102	1104	1107	1109	1112	1114	1117	1119	0	1	1	1	1	2	2	2	2
·05	1122	1125	1127	1130	1132	1135	1138	1140	1143	1146	0	1	1	1	1	2	2	2	2
·06	1148	1151	1153	1156	1159	1161	1164	1167	1169	1172	0	1	1	1	1	2	2	2	2
·07	1175	1178	1180	1183	1186	1189	1191	1194	1197	1199	0	1	1	1	1	2	2	2	3
·08	1202	1205	1208	1211	1213	1216	1219	1222	1225	1227	0	1	1	1	1	2	2	2	3
·09	1230	1233	1236	1239	1242	1245	1247	1250	1253	1256	0	1	1	1	1	2	2	2	2
·10	1259	1262	1265	1268	1271	1274	1276	1279	1282	1285	0	1	1	1	1	2	2	2	3
·11	1288	1291	1294	1297	1300	1303	1306	1309	1312	1315	0	1	1	1	2	2	2	2	3
·12	1318	1321	1324	1327	1330	1334	1337	1340	1343	1346	0	1	1	1	2	2	2	2	3
·13	1349	1352	1355	1358	1361	1365	1368	1371	1374	1377	0	1	1	1	2	2	2	3	3
·14	1380	1384	1387	1390	1393	1396	1400	1403	1406	1409	0	1	1	1	2	2	2	3	3
·15	1413	1416	1419	1422	1426	1429	1432	1435	1439	1442	0	1	1	1	2	2	2	3	3
·16	1445	1449	1452	1455	1459	1462	1466	1469	1472	1476	0	1	1	1	2	2	2	3	3
·17	1479	1483	1486	1489	1493	1496	1500	1503	1507	1510	0	1	1	1	2	2	2	3	3
·18	1514	1517	1521	1524	1528	1531	1535	1538	1542	1545	0	1	1	1	2	2	2	3	3
·19	1549	1552	1556	1560	1563	1567	1570	1574	1578	1581	0	1	1	1	2	2	3	3	3
·20	1585	1589	1592	1596	1600	1603	1607	1611	1614	1618	0	1	1	1	2	2	3	3	3
·21	1622	1626	1629	1633	1637	1641	1644	1648	1652	1656	0	1	1	2	2	2	3	3	3
·22	1660	1663	1667	1671	1675	1679	1683	1687	1690	1694	0	1	1	2	2	2	3	3	3
·23	1698	1702	1706	1710	1714	1718	1722	1726	1730	1734	0	1	1	2	2	2	3	3	4
·24	1738	1742	1746	1750	1754	1758	1762	1766	1770	1774	0	1	1	2	2	2	3	3	4
·25	1778	1782	1786	1791	1795	1799	1803	1807	1811	1816	0	1	1	2	2	2	3	3	4
·26	1820	1824	1828	1832	1837	1841	1845	1849	1854	1858	0	1	1	2	2	3	3	3	4
·27	1862	1866	1871	1875	1879	1884	1888	1892	1897	1901	0	1	1	2	2	3	3	3	4
·28	1905	1910	1914	1919	1923	1928	1932	1936	1941	1945	0	1	1	2	2	3	3	4	4
·29	1950	1954	1959	1963	1968	1972	1977	1982	1986	1991	0	1	1	2	2	3	3	4	4
·30	1995	2000	2004	2009	2014	2018	2023	2028	2032	2037	0	1	1	2	2	3	3	4	4
·31	2042	2046	2051	2056	2061	2065	2070	2075	2080	2084	0	1	1	2	2	3	3	4	4
·32	2089	2094	2099	2104	2109	2113	2118	2123	2128	2133	0	1	1	2	2	3	3	4	4
·33	2138	2143	2148	2153	2158	2163	2168	2173	2178	2183	0	1	1	2	2	3	3	4	4
·34	2188	2193	2198	2203	2208	2213	2218	2223	2228	2234	1	1	2	2	3	3	4	4	5
·35	2239	2244	2249	2254	2259	2265	2270	2275	2280	2286	1	1	2	2	3	3	4	4	5
·36	2291	2296	2301	2307	2312	2317	2323	2328	2333	2339	1	1	2	2	3	3	4	4	5
·37	2344	2350	2355	2360	2366	2371	2377	2382	2388	2393	1	1	2	2	3	3	4	4	5
·38	2399	2404	2410	2415	2421	2427	2432	2438	2443	2449	1	1	2	2	3	3	4	4	5
·39	2455	2460	2466	2472	2477	2483	2489	2495	2500	2506	1	1	2	2	3	3	4	5	5
·40	2512	2518	2523	2529	2535	2541	2547	2553	2559	2564	1	1	2	2	3	4	4	5	5
·41	2570	2576	2582	2588	2594	2600	2606	2612	2618	2624	1	1	2	2	3	4	4	5	5
·42	2630	2636	2642	2649	2655	2661	2667	2673	2679	2685	1	1	2	2	3	4	4	5	6
·43	2692	2698	2704	2710	2716	2723	2729	2735	2742	2748	1	1	2	3	3	4	4	5	6
·44	2754	2761	2767	2773	2780	2786	2793	2799	2805	2812	1	1	2	3	3	4	4	5	6
·45	2818	2825	2831	2838	2844	2851	2858	2864	2871	2877	1	1	2	3	3	4	5	5	6
·46	2884	2891	2897	2904	2911	2917	2924	2931	2938	2944	1	1	2	3	3	4	5	5	6
·47	2951	2958	2965	2972	2979	2985	2992	2999	3006	3013	1	1	2	3	3	4	5	5	6
·48	3020	3027	3034	3041	3048	3055	3062	3069	3076	3083	1	1	2	3	4	4	5	6	6
·49	3090	3097	3105	3112	3119	3126	3133	3141	3148	3155	1	1	2	3	4	4	5	6	6

Antilogarithms

	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
·50	3162	3170	3177	3184	3192	3199	3206	3214	3221	3228	1	1	2	3	4	4	5	6	7
·51	3226	3243	3251	3258	3266	3273	3281	3289	3296	3304	1	2	2	3	4	5	5	6	7
·52	3311	3319	3327	3334	3342	3350	3357	3365	3373	3381	1	2	2	3	4	5	5	6	7
·53	3388	3396	3404	3412	3420	3428	3436	3443	3451	3459	1	2	2	3	4	5	6	6	7
·54	3467	3475	3483	3491	3499	3508	3516	3524	3532	3540	1	2	2	3	4	5	6	6	7
·55	3548	3556	3565	3573	3581	3589	3597	3606	3614	3622	1	2	2	3	4	5	6	7	7
·56	3631	3639	3648	3656	3664	3673	3681	3690	3698	3707	1	2	3	3	4	5	6	7	8
·57	3715	3724	3733	3741	3750	3758	3767	3776	3784	3793	1	2	3	3	4	5	6	7	8
·58	3802	3811	3819	3828	3837	3846	3855	3864	3873	3882	1	2	3	4	4	5	6	7	8
·59	3890	3899	3908	3917	3926	3936	3945	3954	3963	3972	1	2	3	4	5	5	6	7	8
·60	3981	3990	3999	4009	4018	4027	4036	4046	4055	4064	1	2	3	4	5	6	6	7	8
·61	4074	4083	4093	4102	4111	4121	4130	4140	4150	4159	1	2	3	4	5	6	7	8	9
·62	4169	4178	4188	4198	4207	4217	4227	4236	4246	4256	1	2	3	4	5	6	7	8	9
·63	4266	4276	4285	4295	4305	4315	4325	4335	4345	4355	1	2	3	4	5	6	7	8	9
·64	4365	4375	4385	4395	4406	4416	4426	4436	4446	4457	1	2	3	4	5	6	7	8	9
·65	4467	4477	4487	4498	4508	4519	4529	4539	4550	4560	1	2	3	4	5	6	7	8	9
·66	4571	4581	4592	4603	4613	4624	4634	4645	4656	4667	1	2	3	4	5	6	7	9	10
·67	4677	4688	4699	4710	4721	4732	4742	4753	4764	4775	1	2	3	4	5	7	8	9	10
·68	4786	4797	4808	4819	4831	4842	4853	4864	4875	4887	1	2	3	4	6	7	8	9	10
·69	4898	4909	4920	4932	4943	4955	4966	4977	4989	5000	1	2	3	5	6	7	8	9	10
·70	5012	5023	5035	5047	5058	5070	5082	5093	5105	5117	1	2	4	5	6	7	8	9	11
·71	5129	5140	5152	5164	5176	5188	5200	5212	5224	5236	1	2	4	5	6	7	8	10	11
·72	5248	5260	5272	5284	5297	5309	5321	5333	5346	5358	1	2	4	5	6	7	9	10	11
·73	5370	5383	5395	5408	5420	5433	5445	5458	5470	5483	1	3	4	5	6	8	9	10	11
·74	5495	5508	5521	5534	5546	5559	5572	5585	5598	5610	1	3	4	5	6	8	9	10	12
·75	5623	5636	5649	5662	5675	5689	5702	5715	5728	5741	1	3	4	5	7	8	9	10	12
·76	5754	5768	5781	5794	5808	5821	5834	5848	5861	5875	1	3	4	5	7	8	9	11	12
·77	5888	5902	5916	5929	5943	5957	5970	5984	5998	6012	1	3	4	5	7	8	10	11	12
·78	6026	6039	6053	6067	6081	6095	6109	6124	6138	6152	1	3	4	6	7	8	10	11	13
·79	6166	6180	6194	6209	6223	6237	6252	6266	6281	6295	1	3	4	6	7	9	10	11	13
·80	6310	6324	6339	6353	6368	6383	6397	6412	6427	6442	1	3	4	6	7	9	10	12	13
·81	6457	6471	6486	6501	6516	6531	6546	6561	6577	6592	2	3	5	6	8	9	11	12	14
·82	6607	6622	6637	6653	6668	6683	6699	6714	6730	6745	2	3	5	6	8	9	11	12	14
·83	6761	6776	6792	6808	6823	6839	6855	6871	6887	6902	2	3	5	6	8	9	11	13	14
·84	6918	6934	6950	6966	6982	6998	7015	7031	7047	7063	2	3	5	6	8	10	11	13	15
·85	7079	7096	7112	7129	7145	7161	7178	7194	7211	7228	2	3	5	7	8	10	12	13	15
·86	7244	7261	7278	7295	7311	7328	7345	7362	7379	7396	2	3	5	7	8	10	12	13	15
·87	7413	7430	7447	7464	7482	7499	7516	7534	7551	7568	2	3	5	7	9	10	12	14	16
·88	7586	7603	7621	7638	7656	7674	7691	7709	7727	7745	2	4	5	7	9	11	12	14	16
·89	7762	7780	7798	7816	7834	7852	7870	7889	7907	7925	2	4	5	7	9	11	13	14	16
·90	7943	7962	7980	7998	8017	8035	8054	8072	8091	8110	2	4	6	7	9	11	13	15	17
·91	8128	8147	8166	8185	8204	8222	8241	8260	8279	8299	2	4	6	8	9	11	13	15	17
·92	8318	8337	8356	8375	8395	8414	8433	8453	8472	8492	2	4	6	8	10	12	14	15	17
·93	8511	8531	8551	8570	8590	8610	8630	8650	8670	8690	2	4	6	8	10	12	14	16	18
·94	8710	8730	8750	8770	8790	8810	8831	8851	8872	8892	2	4	6	8	10	12	14	16	18
·95	8913	8933	8954	8974	8995	9016	9036	9057	9078	9099	2	4	6	8	10	12	15	17	19
·96	9120	9141	9162	9183	9204	9226	9247	9268	9290	9311	2	4	6	8	11	13	15	17	19
·97	9333	9354	9376	9397	9419	9441	9462	9484	9506	9528	2	4	7	9	11	13	15	17	20
·98	9550	9572	9594	9616	9638	9661	9683	9705	9727	9750	2	4	7	9	11	13	16	18	20
·99	9772	9795	9817	9840	9863	9886	9908	9931	9954	9977	2	5	7	9	11	14	16	18	20

TABLE OF CHORDS, SINES, COSINES, TANGENTS, ETC.

Angle Deg.	Angle Radians	Chords	Sine	Tangent	Cotangent	Cosine			
0°	0	0	0	0	∝	1	1·414	1·5708	90°
1	0·0175	0·017	0·0175	0·0175	57·2900	0·9998	1·402	1·5533	89
2	0·0349	0·035	0·0349	0·0349	28·6363	0·9994	1·389	1·5359	88
3	0·0524	0·052	0·0523	0·0524	19·0811	0·9986	1·377	1·5184	87
4	0·0698	0·070	0·0698	0·0699	14·3007	0·9976	1·364	1·5010	86
5	0·0873	0·087	0·0872	0·0875	11·4301	0·9962	1·351	1·4835	85
6	0·1047	0·105	0·1045	0·1051	9·5144	0·9945	1·328	1·4661	84
7	0·1222	0·122	0·1219	0·1228	8·1443	0·9925	1·325	1·4486	83
8	0·1396	0·139	0·1392	0·1405	7·1154	0·9903	1·312	1·4312	82
9	0·1571	0·157	0·1564	0·1584	6·3138	0·9877	1·299	1·4237	81
10	0·1745	0·174	0·1736	0·1763	5·6713	0·9848	1·286	1·3963	80
11	0·1920	0·192	0·1908	0·1944	5·1446	0·9816	1·272	1·3788	79
12	0·2094	0·209	0·2079	0·2126	4·7046	0·9781	1·259	1·3614	78
13	0·2269	0·226	0·2250	0·2309	4·3315	0·9744	1·245	1·3439	77
14	0·2443	0·244	0·2419	0·2493	4·0108	0·9703	1·231	1·3265	76
15	0·2618	0·261	0·2588	0·2679	3·7321	0·9659	1·217	1·3090	75
16	0·2793	0·278	0·2756	0·2867	3·4874	0·9613	1·204	1·2915	74
17	0·2967	0·296	0·2924	0·3057	3·2709	0·9563	1·190	1·2741	73
18	0·3142	0·313	0·3090	0·3249	3·0777	0·9511	1·176	1·2566	72
19	0·3316	0·330	0·3256	0·3443	2·9042	0·9455	1·161	1·2392	71
20	0·3491	0·347	0·3420	0·3640	2·7475	0·9397	1·147	1·2217	70
21	0·3665	0·364	0·3584	0·3839	2·6051	0·9336	1·133	1·2043	69
22	0·3840	0·382	0·3746	0·4040	2·4751	0·9272	1·118	1·1868	68
23	0·4014	0·399	0·3907	0·4245	2·3559	0·9205	1·104	1·1694	67
24	0·4189	0·416	0·4067	0·4452	2·2460	0·9135	1·089	1·1519	66
25	0·4363	0·433	0·4226	0·4663	2·1445	0·9063	1·075	1·1345	65
26	0·4538	0·450	0·4384	0·4877	2·0503	0·8988	1·060	1·1170	64
27	0·4712	0·467	0·4540	0·5095	1·9626	0·8910	1·045	1·0996	63
28	0·4887	0·484	0·4695	0·5317	1·8807	0·8829	1·030	1·0821	62
29	0·5061	0·501	0·4848	0·5543	1·8040	0·8746	1·015	1·0647	61
30	0·5236	0·518	0·5000	0·5774	1·7321	0·8660	1·000	1·0472	60
31	0·5411	0·534	0·5150	0·6009	1·6643	0·8572	0·985	1·0297	59
32	0·5585	0·551	0·5299	0·6249	1·6003	0·8480	0·970	1·0123	58
33	0·5760	0·568	0·5446	0·6494	1·5399	0·8387	0·954	0·9948	57
34	0·5934	0·585	0·5592	0·6745	1·4826	0·8290	0·939	0·9774	56
35	0·6109	0·601	0·5736	0·7002	1·4281	0·8192	0·923	0·9599	55
36	0·6283	0·618	0·5878	0·7265	1·3764	0·8090	0·908	0·9425	54
37	0·6458	0·635	0·6018	0·7536	1·3270	0·7986	0·892	0·9250	53
38	0·6632	0·651	0·6157	0·7813	1·2799	0·7880	0·877	0·9076	52
39	0·6807	0·668	0·6293	0·8098	1·2349	6·7771	0·861	0·8901	51
40	0·6981	0·684	0·6428	0·8391	1·1918	0·7660	0·845	0·8727	50
41	0·7156	0·700	0·6561	0·8963	1·1504	0·7547	0·829	0·8552	49
42	0·7330	0·717	0·6691	0·9004	1·1106	0·7431	0·813	0·8378	48
43	0·7505	0·733	0·6820	0·9325	1·0724	0·7314	0·797	0·8203	47
44	0·7679	0·749	0·6947	0·9657	1·0355	0·7193	0·781	0·8028	46
45	0·7854	0·765	0·7071	1·0000	1·0000	0·7071	0·965	0·7854	45
			Cosine	Cotangent	Tangent	Sine	Chords	Angle Radians	Angle Deg.

Tables of logarithems, antilogarithems, chords, sines, cosines and antitangents (reproduced by permission of E. & F. N. Spon Ltd.).

CONVERSION FACTORS

Inches to centimetres	multiply by	2·540
Feet to metres	,, ,,	0·3048
Square inches to square centimetres ..	,, ,,	6·4516
Square feet to square metres	,, ,,	0·0929
Circular mils to square inches	,, ,,	$0{\cdot}7854 \cdot 10^{-6}$
Circular mils to square millimetres ..	,, ,,	$0{\cdot}5067 \cdot 10^{-3}$
Cubic inches to cubic centimetres ..	,, ,,	16·387
Cubic feet to cubic metres	,, ,,	0·028 32
Short tons to tons	,, ,,	0·893
Pounds to kilogrammes	,, ,,	0·4536
Tons to kilogrammes	,, ,,	1 016·05
Pounds per square inch to kilogrammes per square millimetre	,, ,,	0·000 703 1
Atmospheres to pounds per square inch ..	,, ,,	14·73
Miles per hour to feet per second ..	,, ,,	1·466 7
Miles per hour to metres per second ..	,, ,,	0·447 03
Gramme calories to British Thermal Units	,, ,,	0·003 968
Gramme calories to joules (watt-seconds)	,, ,,	4·186
British Thermal Units to joules (watt-seconds)	,, ,,	1 054·8
Microhms per sq. cm. per cm. to microhms per sq. in. per ft.	,, ,,	4·724 4
Microhms per sq. cm. per cm. to ohms per mil foot	,, ,,	6·015 3
Fahrenheit to Centigrade, Subtract 32, ..	,, ,,	5/9
Centigrade to Fahrenheit, Multiply by 9/5,	Add	32
Resistance of copper at 60°F to resistance at 20°C	multiply by	1·017 8
Resistance of copper at 20°C to resistance at 60°F	,, ,,	0·982 5

20°C = 68°F 60°F = 15·6°C approximately

TABLE OF DECIMAL PREFIXES AND SYMBOLS

Unit	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

STANDARD DIAGRAMS

Some standard diagrams respecting shunt and compound wound d.c. generators, Board of Trade wiring systems, and instrument connections are illustrated thoughout the ensuing pages of this appendix.

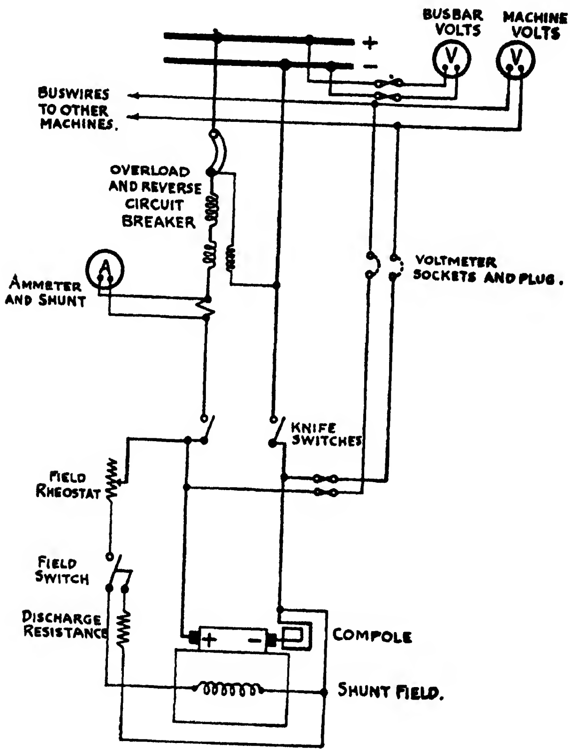


FIG. C-1.—*Two wire shunt wound d.c. generator.*

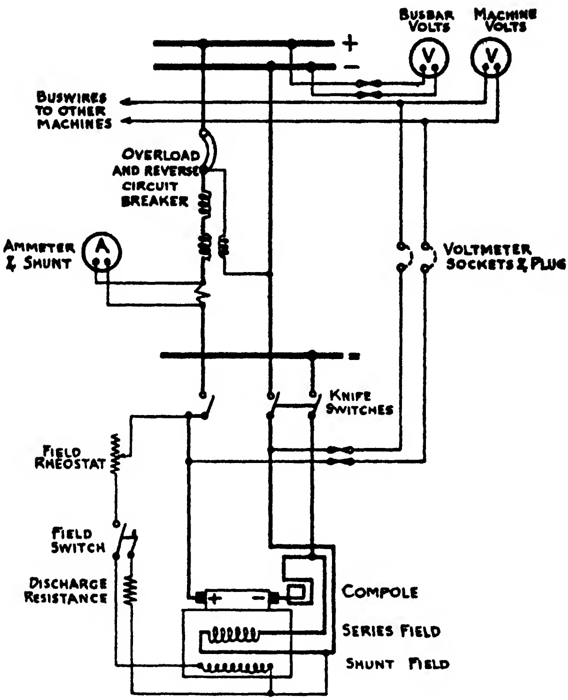


FIG. C-2.—*Two wire compound wound d.c. generator.*

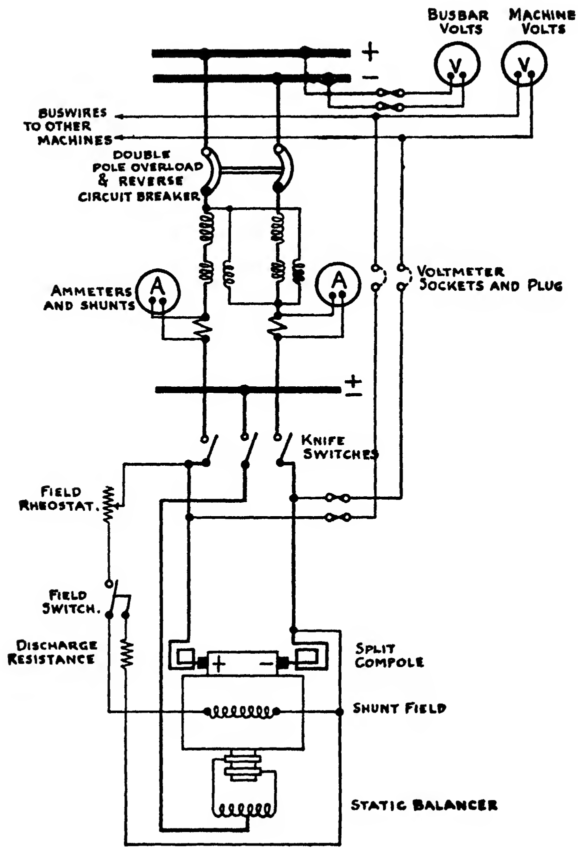


FIG. C-3.—*Three wire shunt wound d.c. generator.*

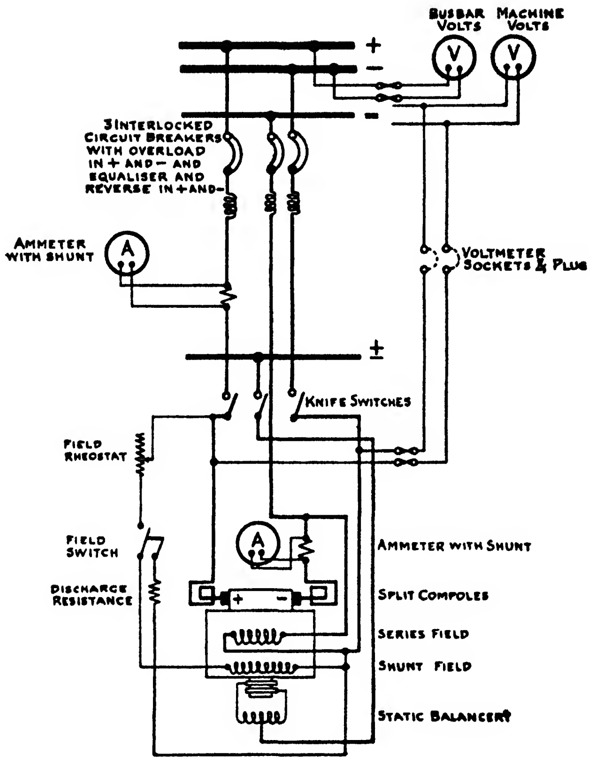


FIG. C-4.—*Three wire compound wound d.c. generator.*

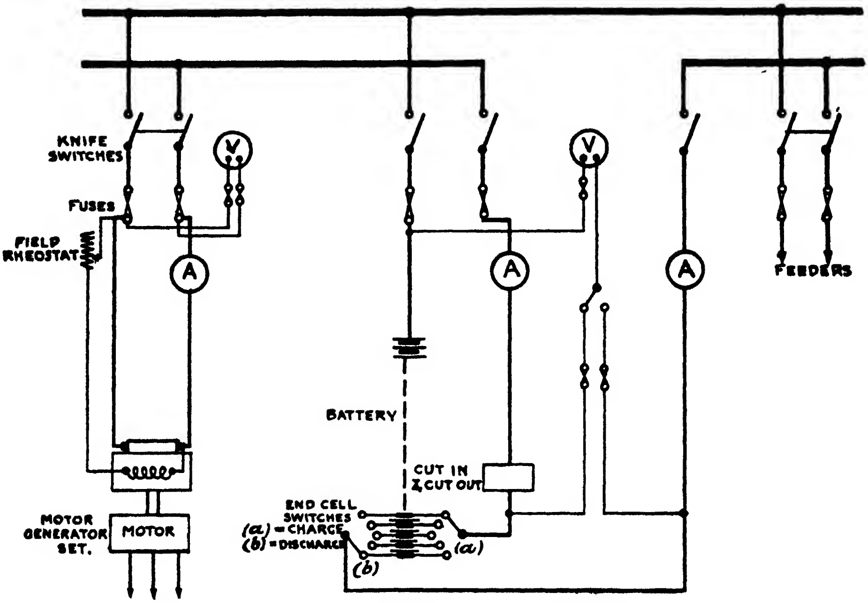


FIG. C-5.—*Diagram of connections for typical battery panel.*

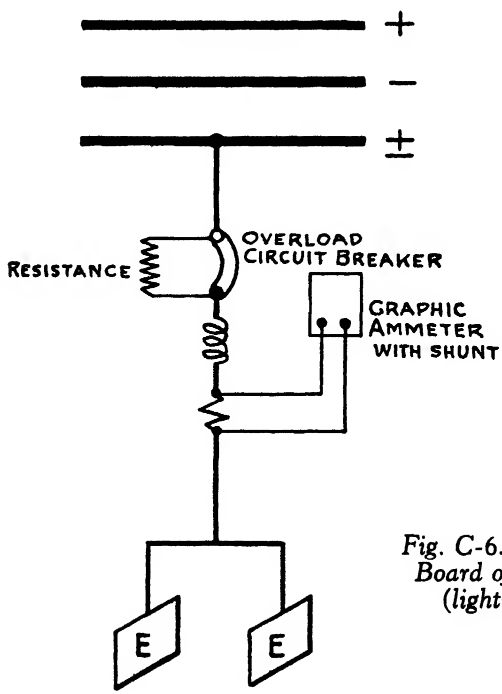


Fig. C-6.—Diagram of Board of Trade panel (lighting system).

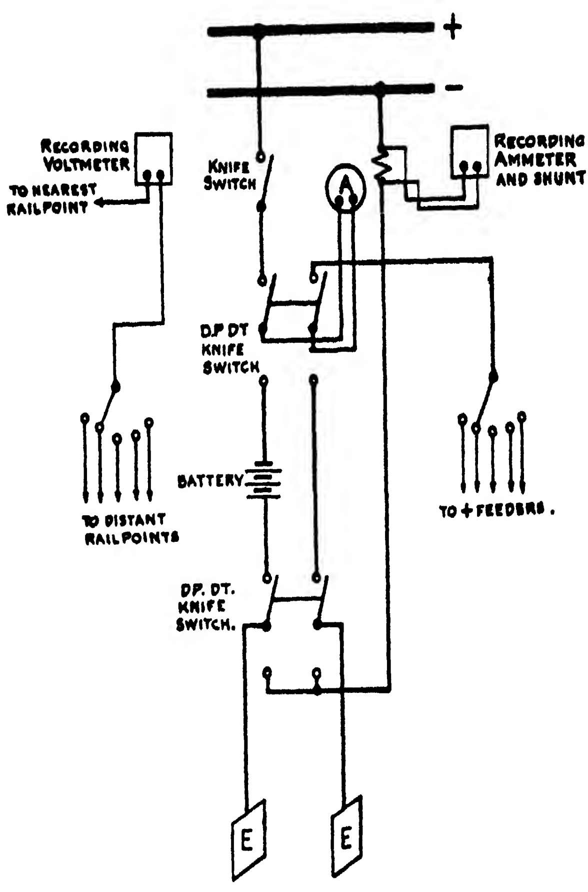


FIG. C-7.—*Diagram of Board of Trade panel (traction system).*

INSTRUMENT CONNECTIONS

When studying the following instrument connection diagrams Figs. C-8 to C-22 inclusive it should be noted that—
Phases must come up in order A, B, C, for three phase systems.
Phases must come up in order A, B, for two phase systems.

X=Direct voltage connection.
Y=Voltage connection through voltage transformer.
Z=Voltage connection through resistance box.
W=Combination of Y and Z.

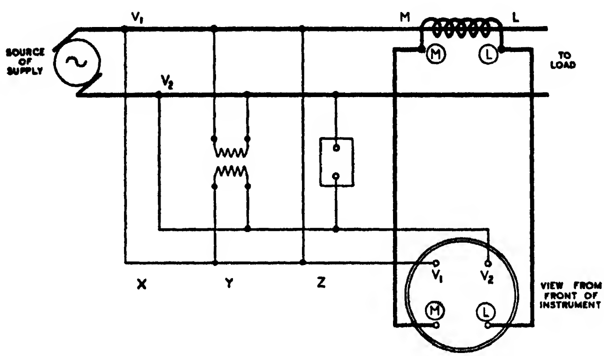


FIG. C-8.—*Connections for single phase power factor meter (Messrs. Nalder Bros. and Thompson Ltd.).*

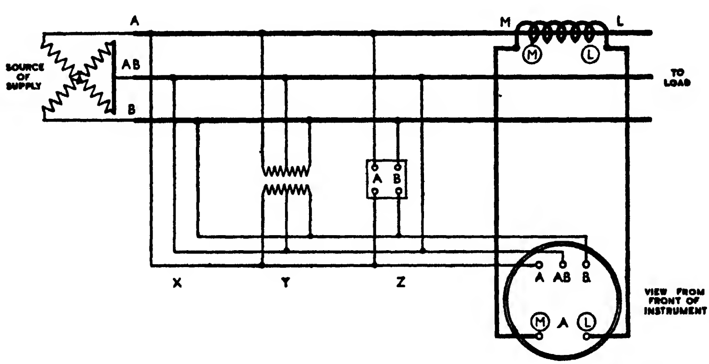


FIG. C-9.—*Connection for two phase balanced load power factor meter (one current and two voltage elements) (Messrs. Nalder Bros. and Thompson Ltd.).*

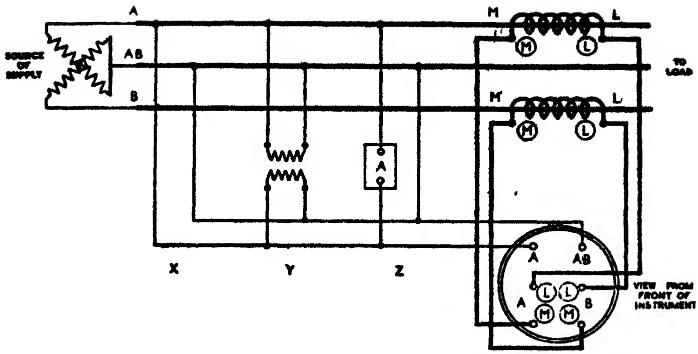


FIG. C-10.—*Connections for two phase balanced load power factor meter (two current and one voltage elements) Messrs. Nalder Bros. and Thompson Ltd.).*

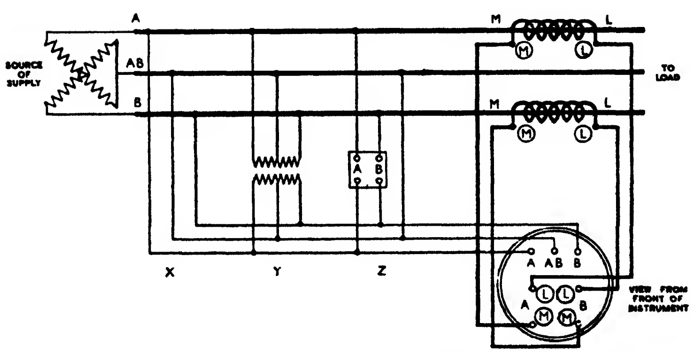


FIG. C-11.—*Connections for two phase unbalanced load power factor meter (Messrs. Nalder Bros. and Thompson Ltd.).*

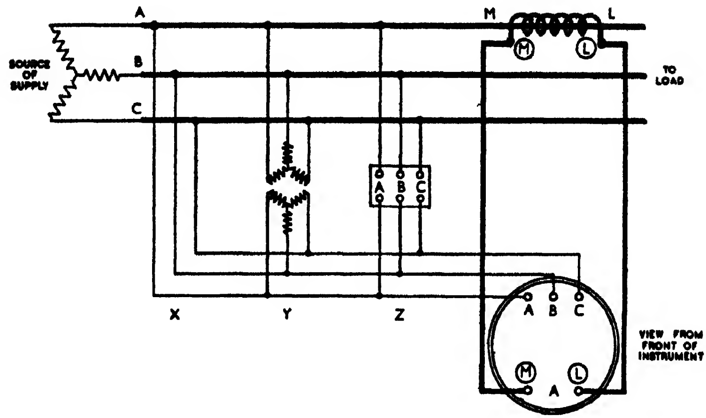


FIG. C-12.—*Connections for three phase balanced load power factor meter (one current and three voltage elements) (Messrs. Nalder Bros. and Thompson Ltd.).*

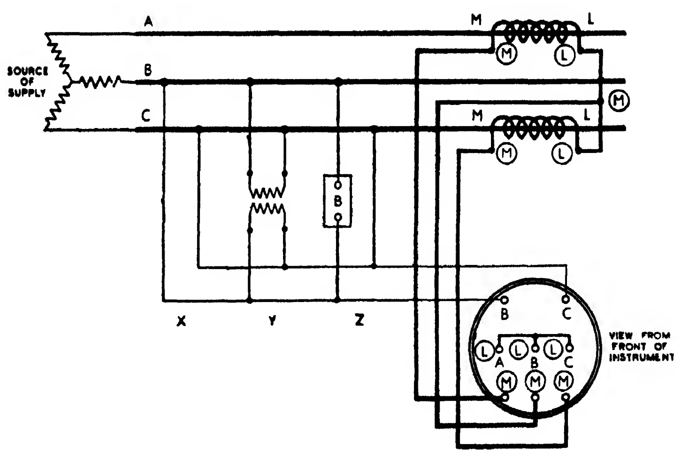


FIG. C-13.—*Connections for three phase balanced load power factor meter (three current and one voltage element) (Messrs. Nalder Bros. and Thompson Ltd.).*

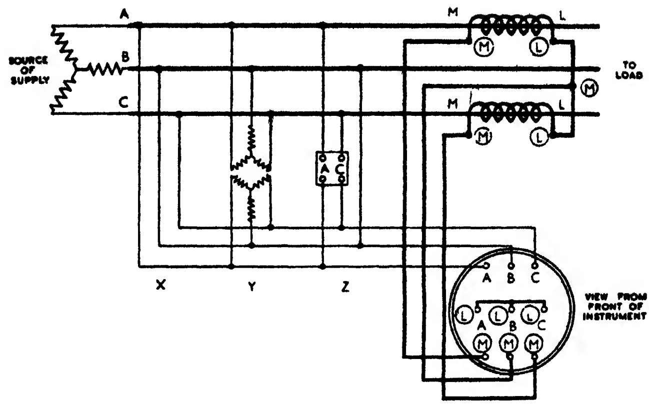


FIG. C-14.—*Connections for three phase three wire unbalanced load power factor meter (Messrs. Nalder Bros. and Thompson Ltd.).*

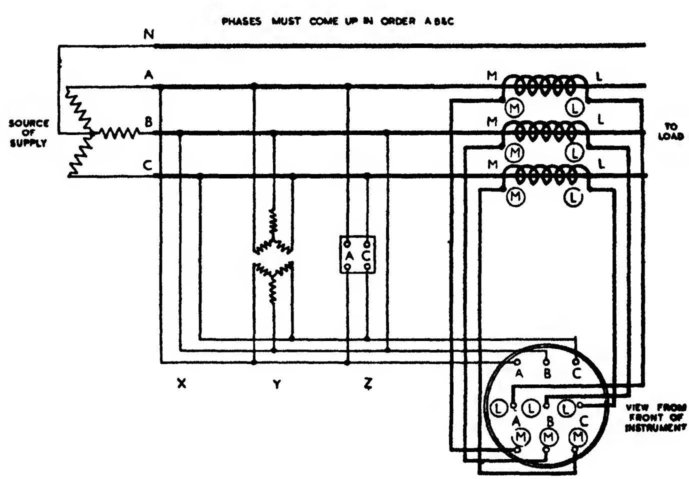


FIG. C-15.—*Connections for three phase four wire unbalanced load power factor meter (Messrs. Nalder Bros and Thompson Ltd.).*

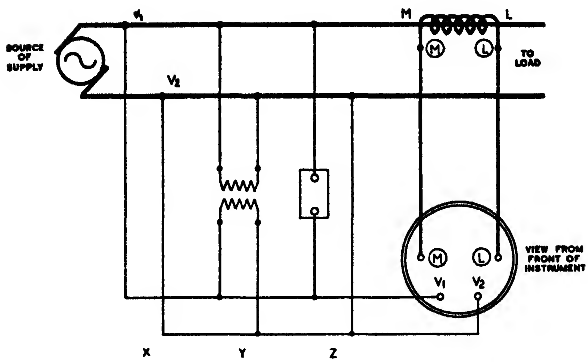


FIG. C-16.—*Connections for single phase indicating wattmeter (Messrs. Nalder Bros. and Thompson Ltd.).*

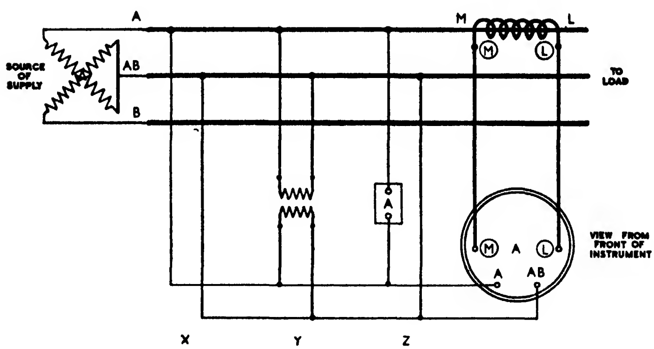


FIG. C-17.—*Connections for two phase balanced load indicating wattmeter (Messrs. Nalder Bros. and Thompson Ltd.).*

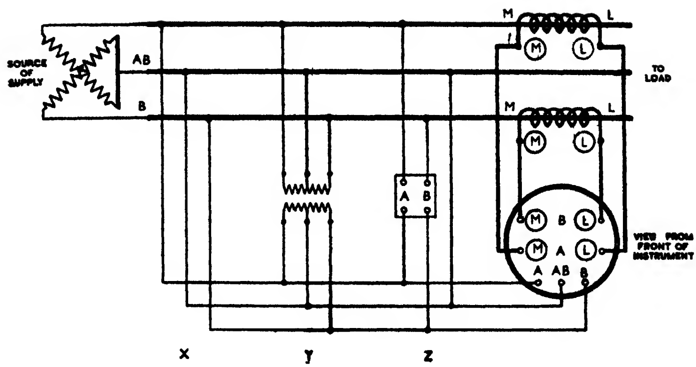


FIG C-18 —*Connections for two phase unbalanced load indicating wattmeter (Messrs Nalder Bros. and Thompson Ltd).*

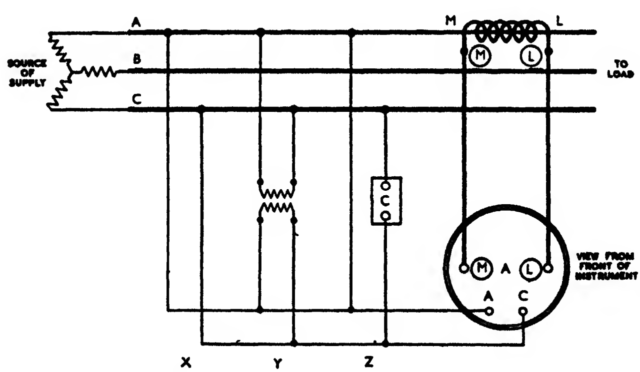


FIG C-19 —*Connections for three phase balanced load indicating wattmeter (Messrs Nalder Bros and Thompson Ltd).*

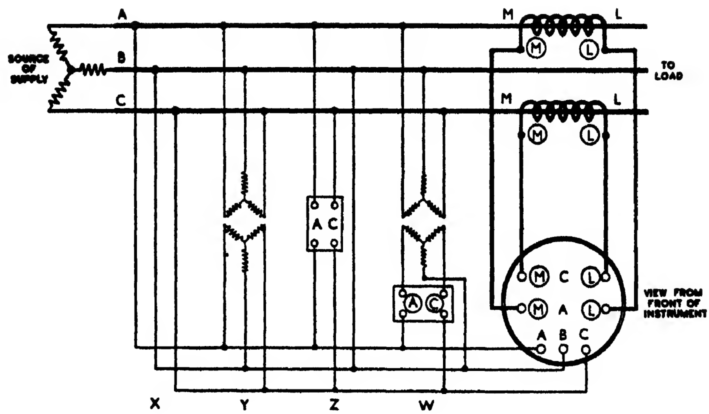


FIG. C-20.—*Connections for three phase three wire unbalanced load indicating wattmeter (Messrs. Nalder Bros. and Thompson Ltd.).*

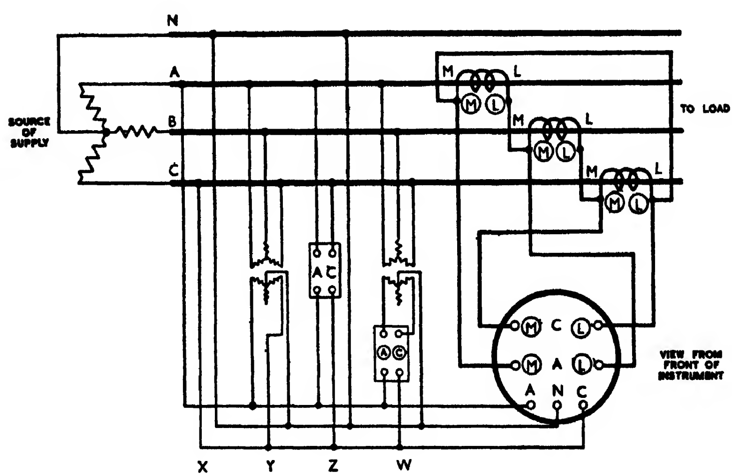


FIG. C-21.—*Connections for three phase four wire unbalanced load indicating wattmeter (two element type) (Messrs. Nalder Bros. and Thompson Ltd.).*

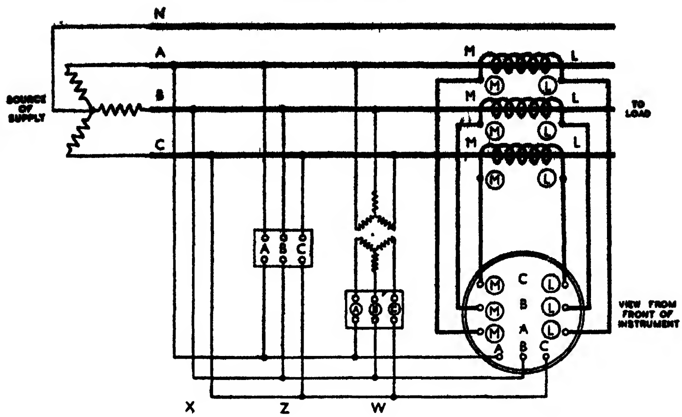
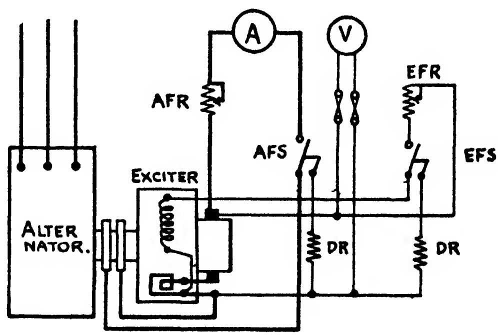


FIG. C-22.—*Connections for three phase four wire unbalanced load indicating wattmeter (three element type) (Messrs. Nalder Bros. and Thompson Ltd.).*

NOTE.—ONLY ONE FIELD SWITCH IS NECESSARY EITHER IN THE EXCITER OR MAIN FIELD.

THE DISCHARGE RESISTANCE IN THE MAIN FIELD MAY BE DISPENSED WITH FOR CERTAIN DESIGNS OF ALTERNATOR.

THE RHEOSTAT IN THE MAIN FIELD IS OPTIONAL



A	AMMETER.
V	VOLTMETER.
AFR	ALTERNATOR FIELD RHEOSTAT
EFR	EXCITER FIELD RHEOSTAT.
AFS	ALTERNATOR FIELD SWITCH.
EFS	EXCITER FIELD SWITCH.
DR	DISCHARGE RESISTANCES

FIG. C-23.—*Diagram of alternator field equipment.*

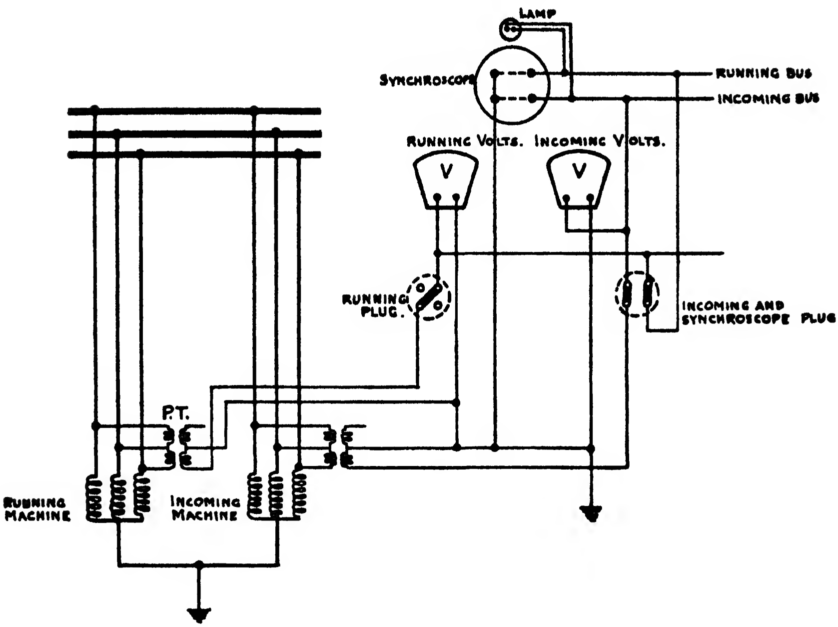


FIG. C-24.—*Typical synchronising connections—synchronising between machines and lamp dark at synchronism.*

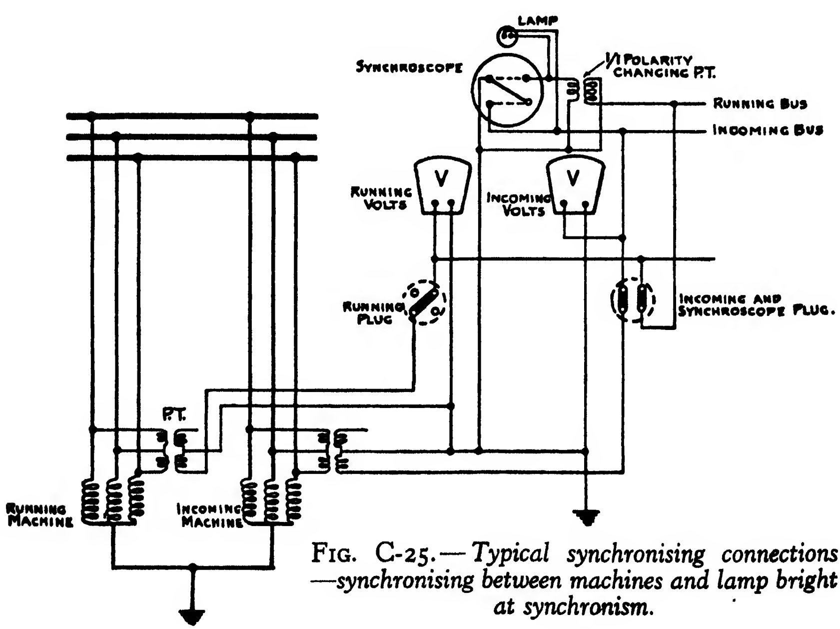


FIG. C-25.—*Typical synchronising connections—synchronising between machines and lamp bright at synchronism.*

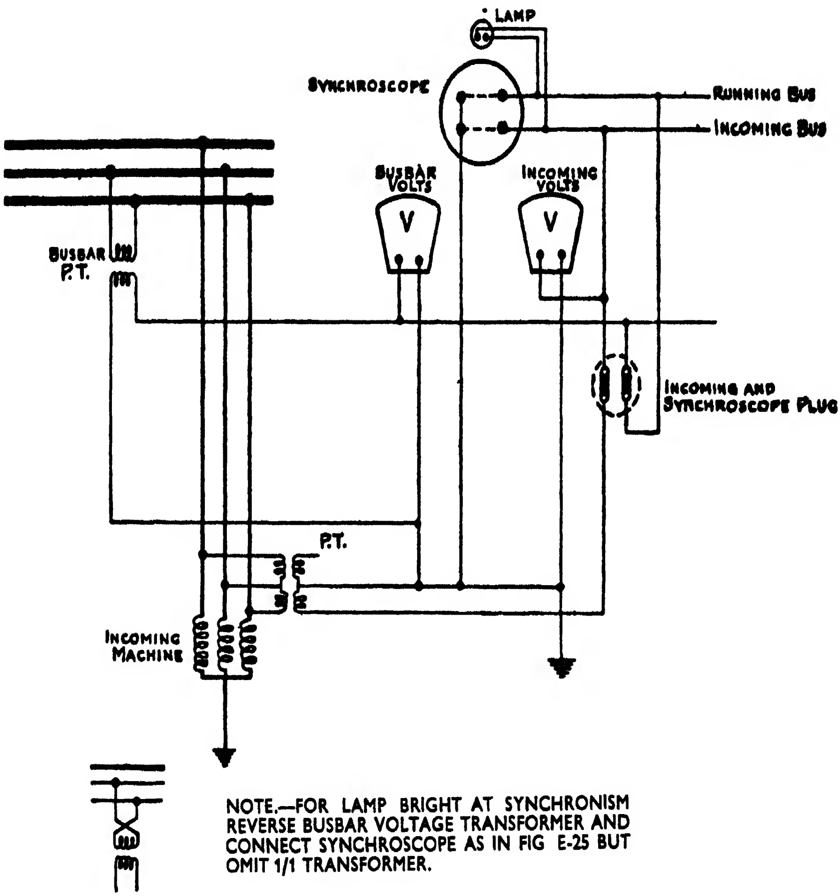


FIG. C-26.—*Typical cynchronising connections—synchronising between busbars and machines and lamp dark at synchronism.*

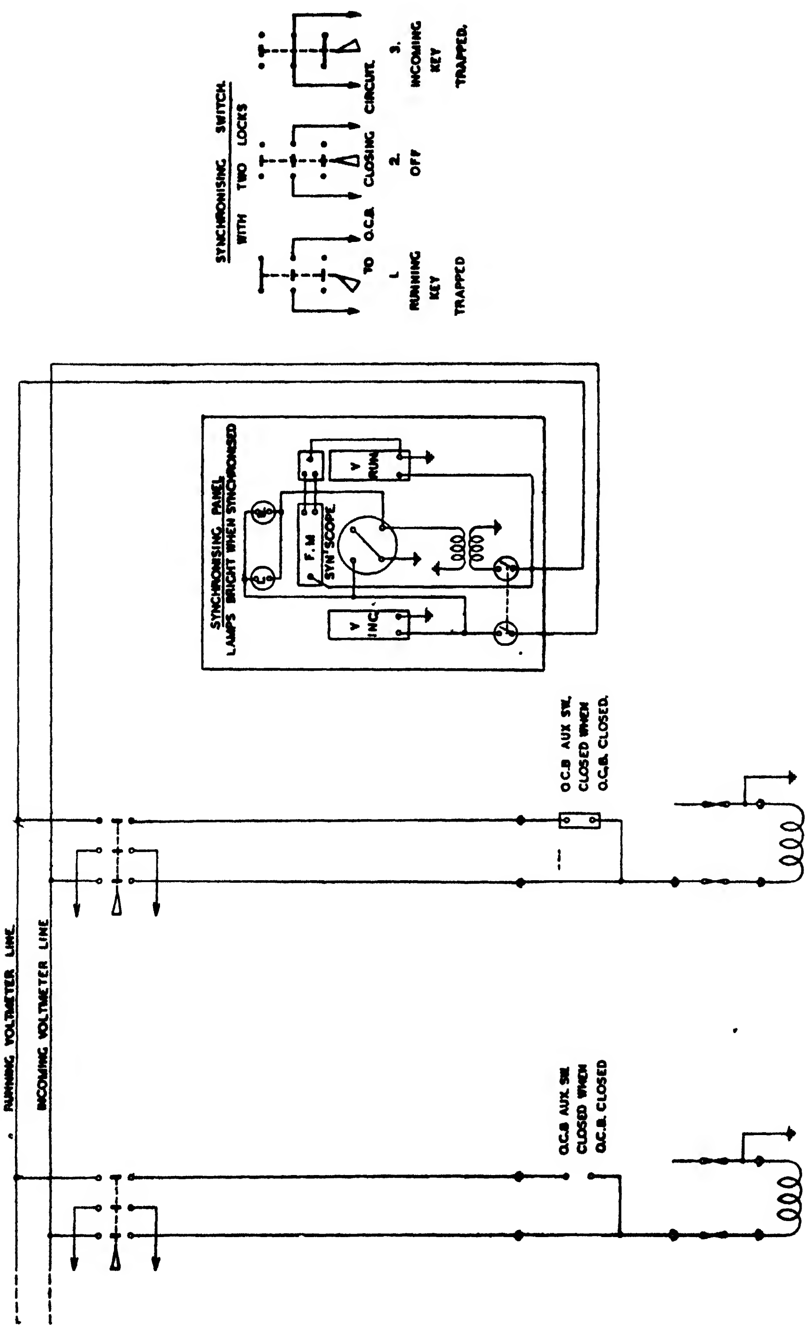


FIG. C-27.—*Synchronising scheme using key interlocked control switches.*

INDEX

A

B

C

D

E

F

G

H

I

J

K

L

M

T

U

V

W

Z

Printed in England by JAMES COND LTD.,
Birmingham and London.